NEW ELEMENTARY PHYSICS

DOMESTIC PHYSICS BEFORE GALILEO

Daughters holding father in the boat as he wings the dinner-duck
From a wall painting in the tomb of Nakht at Thebes
Courtesy of the Metropolitan Museum of Art

New ELEMENTARY PHYSICS

By

ROBERT ANDREWS MILLIKAN, PH.D., SC.D.

HENRY GORDON GALE, PH.D.

and

JAMES P. COYLE, M.E.

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physics without obscuring the supremely significant fact that the new knowledge has practically always grown out of the old knowledge, supplementing and extending it rather than replacing it. It is this continually growing store of *accumulated and well-tested knowledge* that alone makes possible the progress of civilization.

The third new condition has also been created by the influx into the secondary school of practically the whole population of suitable age. It is found in the demand for a greater flexibility in the physics course in order that it may be adapted to the groups of students of widely varying preparation, background, and objective now found in the high school, all of whom are in sore need of its influence. To meet this need of flexibility and to give the teacher a relatively large choice of material there are found in these pages three distinct courses. The simplest and most elementary, suitable for almost any group or grade in the secondary school, is carried by the paragraphs that are not differentiated by the symbol [. The *A* problems and problems not designated either as *A* or as *B* are especially designed to accompany this most elementary course, a course which might be called the indispensable backbone of such a presentation as would generally be given to groups that have the least time to spend on physics. Special care has been taken to give this course the greatest possible simplicity and directness of presentation. For groups that have more time and can do the work more thoroughly there may be added to this course as many of the optional paragraphs preceded by the symbol [, and as many of the *B* problems, as the teacher may think desirable.

In addition to these two systematic courses and as an aid to both of them, the pedagogical expedient, already successfully tried in a less complete way, has been adopted of presenting an *incidental picture course* on the history of physics, and especially on its modern industrial applications. This consists of a hundred and twenty-six full-page illustrations, with rather elaborate and complete explanatory legends. No attempt has been made to make these illustra-

tions an organic part of the systematic course presented in the text pages. They are introduced, rather, for the sake of arresting the student's attention, stimulating his interest, and getting before him incidentally a large number of fascinating facts and developments which he may not completely understand but which will nevertheless arouse his interest, stimulate him to further study, and give him problems of his own to work on. The pupil who is capable of doing more and understanding better than the average run of the class should profit very greatly by this feature. A second advantage that it offers arises from the fact that almost every teacher has some particular industrial development in which he is especially interested, and which often for local reasons he wishes to incorporate into his course, sometimes even when it is beyond the proper scope of an elementary course organized for the average pupil. Such a teacher can incorporate as many of these illustrations in the systematic course as he wishes.

Acknowledgments are due to hundreds of teachers who have assisted us by trying out in the school of experience not merely our content, but also our mode of presentation. We have had special assistance from E. C. Pritchard, head of the electrical construction department, from William A. Sears, head of the automobile department, and from the eight members of the physics department of the Lane Technical High School, Chicago, who have read parts of the proof and have given valuable suggestions in the course of the revision. We would also acknowledge expert assistance from Messrs. J. B. Hoag, S. S. Mackeown, R. W. Sorensen, C. B. Millikan, M. F. Millikan, and a large group of engineers of the General Electric Company and the American Telephone and Telegraph Company, who have added greatly to the correctness and accuracy of our presentation of the fields in which they are experts.

R. A. M.
H. G. G.
J. P. C.

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Primitive man heard the whispering of the wind and the rush of the storm; he felt the buoyancy of the sea and the terrible power of its waves. Not understanding these things or being able to control them, he imagined the existence of invisible beings, much like himself, but much more powerful, who could and did control them to their own ends.

These beings were his gods. In the Greco-Roman world the god of the winds was called Aeolus, and the god of the sea Neptune (or Poseidon).

This first unit of physics tells us how men came gradually to understand more and more about the laws of air and other gases and the laws of liquids. Perhaps we are justified in saying that the earliest physicist was Archimedes of Syracuse (third century B.C.). His discovery of some of the laws of liquids began the gradual replacement of the superstitious fear of the wind and the waves by a rational understanding of the properties of fluids.

Unit II · Laws of Force and Motion

Through all the days of savagery man had used force to produce motion. He first struck down his quarry with a club; then he slowly learned to stand off and hurl a stone, then a spear, then a dart, then an arrow, and finally a bullet. Also, through all the days of the existence of the amazing civilizations of Egypt, Greece, Rome, China, and India, men had continually used force to produce motion for other pur-

poses than those of the hunt — for example, they had pushed carts and pulled wagons; but up to about the age in which Galileo lived (1600 A.D.) not one of them, so far as we know, had gained any correct understanding of the relations between force and motion. The second unit of our study tells the fascinating story of how, during the past four hundred years, man has slowly gained a knowledge of the laws of force and motion, and through the application of this knowledge has ushered in the era of modern mechanical civilization, in which machines do most of the work that was formerly done by human slaves.

Unit III · Work and Heat

For thousands of years man had warmed himself by his campfire and cooked his food in its embers without ever finding out anything about the nature of heat and its laws. It was not until the laws of force and motion were discovered that man could understand the laws of heat and so could learn to use it and control it in a scientific way. Practically all the third unit deals with knowledge (acquired since about 1800 A.D.) of the conditions under which machines can be used to do useful work.

Unit IV · Electricity and Magnetism

Until about two hundred years ago mankind knew little more about the nature of the lightning's flash or the roll of thunder than did the ancients. The thunderbolt inspired merely awe and superstitious fear. We no longer feel that there is anything supernatural about a thunderstorm. Today six million people in the United States alone earn their daily bread directly or indirectly through the electrical industry, and practically every inhabitant of the country is served continually by electrical appliances of one sort or another. The fourth unit tells how electricity has been set to work for the benefit of mankind.

Unit V Sound and Wave Motion

Sound is at the same time the oldest and the newest of the fields of physics. Primitive man called loudly to his fellows when he encountered danger or found food. Today the newly developed sound pictures draw millions of people in the United States each week to see and hear them. Again, music plays an enormous role in the life of modern man, but the mechanics of music cannot be properly understood without a knowledge of the elements of sound. Then there is the subject of wave motion, which is best comprehended through its applications in the field of sound; and every boy and girl needs to know something about it to live at all intelligently today.

Unit VI · Light

To live in a world of light and know nothing about what it is and what are the laws that govern it is to an intelligent person unthinkable. The Greeks attributed light rays to Apollo, the god of the sun. They learned practically nothing about them, however, because the days of even the beginnings of man's understanding of nature had not yet arrived. Man's life and conduct were dictated mainly by his fears and his superstitions. It was the study of light, the sixth unit, that paved the way for and made possible the understanding of the newer developments of twentieth-century physics that are treated in the seventh and last unit.

Unit VII · Electronics and Invisible Radiations

Here we enter the field of the discoveries of the twentieth century, which so dominate the lives of everyone today. We learn about the amplifier tube, the radio, X rays, radioactivity, cosmic rays, and also about electrons (positive and negative), neutrons, deuterons, protons, and photons.

In a word, then, the study of physics through our seven units is merely the story of man's slow release from the ignorance and fear and superstition and fatalism that surrounded and engulfed him in former times, and his gradual development of the conviction that he himself can, partially at least, understand and can to some extent control the world and his destiny in it.

The study of physics is, indeed, of enormous practical importance for the daily life of every man and woman; but its importance goes far beyond this. It has taught man not to fear his surroundings but by understanding them to control them. It has taught him that by scientifically examining his superstitions he can banish his fears. And what does this scientific method involve? It involves refusing to conduct our lives according to prejudice, emotion, whim, or superstition. It involves withholding judgments until we know all the facts. If we ourselves have no opportunity to study a problem, it involves taking as advisers only those who have had such opportunity and who have also themselves formed the habit of using the scientific method. There is no study that gives a better training in the use of that method than the study of the elements of physics.

CHAPTER I

Measurement

Fundamental Units

Introductory. Our accurate knowledge about natural phenomena has been acquired chiefly through careful measurements. This applies to practically everything we wear, eat, or use. The modern speedy, low-priced automobiles would be impossible were it not for accurate measurements permitting interchangeability of parts on the assembly line. The ability of man to control his surroundings depends on the degree of exactness with which he measures the variables involved. We can measure three fundamentally different kinds of quantities, — length, mass, and time, — and we shall find that all other measurements may be reduced to these three. Our first problem in physics is, then, to learn something about the units in terms of which all our physical knowledge is expressed.

The historic standard of length. Nearly all civilized nations have at some time used a unit of length the name of which meant the same as *foot* in English. There can scarcely be any doubt, therefore, that in each country this unit has been derived from the length of the human foot. The *yard* is supposed to have represented the length of the arm of an English king, Henry I. After this unit became established as a standard, it is probable that the foot was arbitrarily chosen as one third of the yard. In view of such an origin it will be clear why no agreement existed among the units in use in different countries.

Relations between different units of length. It has also been true, in general, that in a given country the different units of length in common use (such, for example, as the inch,

the hand, the foot, the fathom, the rod, the mile) have been derived either from the lengths of different parts of the human body or from equally unrelated magnitudes, and in consequence have been connected with one another by different, and often by very awkward, multipliers. Thus there are 12 inches in a foot, 3 feet in a yard, $5\frac{1}{2}$ yards in a rod, 320 rods in a mile, etc.

Relations between units of length, area, volume, and mass. A similar and even worse complexity exists in the relations of the units of length to those of area, volume, and mass. Thus there are $272\frac{1}{4}$ square feet in a square rod, $57\frac{3}{4}$ cubic inches in a quart, and $31\frac{1}{2}$ gallons in a barrel. Again, the pound, instead of being the mass of a cubic inch or a cubic foot of water or of some other common substance, is the mass of a cylinder of platinum, of inconvenient dimensions, which is preserved in London.

Origin of the metric system. At the time of the French Revolution the extreme inconvenience of existing weights and measures, together with the confusion arising from the use of different standards in different localities, led the National Assembly of France to appoint a commission to devise a more logical system. The result of the labors of this commission was the present metric system, which was introduced into France in 1793 and has since been adopted by the governments of most civilized nations except those of Great Britain and the United States; and even in these countries its use in scientific work is practically universal. The World War did much to speed its adoption. A number of bills proposing its use have been brought up in Congress; but owing to the tremendous expense involved and to other factors they have so far failed to pass.

The standard meter. The standard *length* in the metric system is called the *meter* (m*). It is the distance, at the freezing temperature, between two transverse parallel lines ruled on a bar of platinum-iridium (Fig. 1), which is kept

* With such an abbreviation a period will not be used unless the abbreviation is also an English word, as *in.* for "inch."

at the International Bureau of Weights and Measures at Sèvres, near Paris. *This distance is 39.37 inches* (Fig. 2).

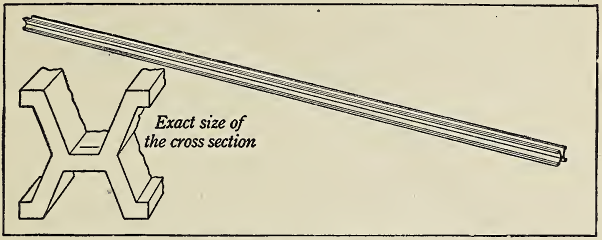


FIG. 1. The standard meter

In order that this standard length might be reproduced if lost, the commission attempted to make it one ten-millionth of the distance from the equator to the north pole, measured

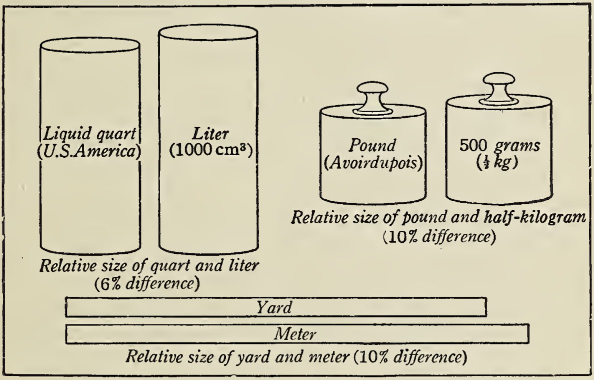


FIG. 2. Metric units in comparison with the old unstandardized units

on the meridian of Paris. But since later measurements have thrown some doubt upon the exactness of the commission's measurement of this distance, we now define the meter not as any particular fraction of the earth's quadrant, but simply as the distance between the scratches on the bar mentioned

above. On account of its more convenient size the centimeter (one one-hundredth of a meter) is universally used, for scientific purposes, as the fundamental unit of length.

Metric standard of capacity. The French or German housewife buys her milk by the liter (l), not the quart. The liter is the standard unit of capacity, and is the volume of a cube which is one tenth of a meter (about 4 inches) on a side. *The liter is therefore equal to 1000 cubic centimeters* (cm^3). It is equivalent to 1.057 quarts (see Fig. 2).

The metric standard of mass. In order to establish a connection between the unit of length and the unit of mass, the commission directed a committee of the French Academy to prepare a cylinder of platinum which should have the same weight as a liter of water at its temperature of greatest density, namely, 4° centigrade (39° Fahrenheit). An exact equivalent of this cylinder, made of platinum-iridium and kept at Sèvres with the standard meter, now represents the standard of mass in the metric system. It is called the *standard kilogram* (kg) and is equivalent to about 2.2 pounds. One one-thousandth of this mass was adopted as the fundamental unit of mass and was named the *gram* (g). For practical purposes, therefore, *the gram may be taken as equal to the mass of 1 cubic centimeter of water.*

The other metric units. The three standard units of the metric system — the meter, the liter, and the gram — have decimal multiples and submultiples, so that every unit of length, volume, or mass is connected with the unit of next higher denomination by the same multiplier, namely ten.

The names of the multiples are obtained by adding the prefixes *deka* (ten), *hecto* (hundred), *kilo* (thousand); the submultiples are formed by adding the prefixes *deci* (tenth), *centi* (hundredth), and *milli* (thousandth). Thus:

1 dekameter = 10 meters	1 decimeter = $\frac{1}{10}$ meter
1 hectometer = 100 meters	1 centimeter = $\frac{1}{100}$ meter
1 kilometer = 1000 meters	1 millimeter = $\frac{1}{1000}$ meter

Written in another form the metric table of length becomes

10 millimeters = 1 centimeter	10 meters = 1 dekameter
10 centimeters = 1 decimeter	10 dekameters = 1 hectometer
10 decimeters = 1 *meter*	10 hectometers = 1 kilometer

Changing "meters" or "meter" to "liters" or "liter" in the table above, we have the table of capacity. Substitute "grams" or "gram," and we have the table of mass. These are much easier to remember than the corresponding tables in the English system, and the arithmetic of changing from one value to another is much simpler. To change 1037 millimeters to meters, one moves the decimal point three places to the left to obtain the answer, 1.037 meters. Compare this with the work necessary to change 1037 feet to miles.

The most common of these units, with the abbreviations which will be used for them in this book, are the following:

meter (m)	liter (l)
kilometer (km)	cubic centimeter (cm^3)
centimeter (cm)	gram (g)
decimeter (dm)	kilogram (kg)
millimeter (mm)	milligram (mg)
dekameter (dkm)	

Relations between the English and metric units. The following table, *which is inserted for reference only*, gives the relation between the most common English and metric units:

1 inch (in.) = 2.54 cm	1 cm = .3937 in.
1 foot (ft) = 30.48 cm	1 m = 1.094 yd = 39.37 in.
1 mile (mi) = 1.609 km	1 km = .6214 mi
1 grain = 64.8 mg	1 g = 15.44 grains
1 oz av = 28.35 g	1 g = .0353 oz
1 lb av = .4536 kg	1 kg = 2.204 lb

The relations 1 in. = 2.54 cm, 1 m = 39.37 in., 1 kg = 2.2 lb, 1 km = .62 mi, should be memorized. Portions of a centimeter

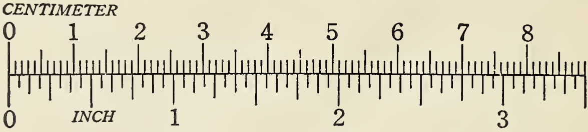


FIG. 3. Centimeter and inch scales

and of an inch scale are shown together in Fig. 3. It will be seen from Fig. 3 that 1 inch = 2.54 centimeters, or 25.4 millimeters.

The standard unit of time. The *second* is taken among all the civilized nations as the standard unit of time. It is $\frac{1}{86,400}$ part of the mean solar day; that is, of the average time from noon to noon.

Measurement of length. Measuring the length of a body consists simply in comparing its length with that of the standard meter bar kept at the International Bureau. In order that this may be done conveniently, great numbers of rods of the same length as this standard meter bar have been made and distributed all over the world. They are our common meter sticks. They are divided into 10, 100, or 1000 equal parts. Great care is taken to have all the parts of exactly the same length.

Measurement of mass. Similarly, measuring the mass of a body consists in comparing its mass with that of the standard kilogram. In order that this might be done conveniently it was necessary first to construct bodies of the same mass as this kilogram, and then to make a whole series of bodies whose masses were $\frac{1}{2}$, $\frac{1}{10}$, $\frac{1}{100}$, $\frac{1}{1000}$, etc. of the mass of this kilogram; in other words, to construct a set of standard masses commonly called a *set of weights* (Fig. 4).

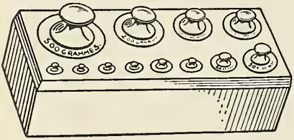


FIG. 4. A set of weights

With the aid of such a set of standard masses the determination of the mass of an unknown body may be made by placing the body upon the pan B (Fig. 5), counterpoising by adding shot, paper, etc. to the pan A, and then replacing the unknown body at B by as many of the standard masses as are required to bring the pointer back to O again. The mass of the body is equal to the sum of these standard masses. This rigorously correct method of weighing is called the *method of substitution.*

If a balance is well constructed, however, a weighing may usually be made with sufficient accuracy by simply placing the unknown body upon one pan and finding the sum of the standard masses which must then be placed upon the other pan to bring the pointer again to O. This is the usual method of weighing. It gives correct results only when the knife-edge C is exactly midway between the points of support m and n of the two pans. *It is customary to consider that the mass of a body, determined as here indicated, is a measure of the quantity of matter which it contains.*

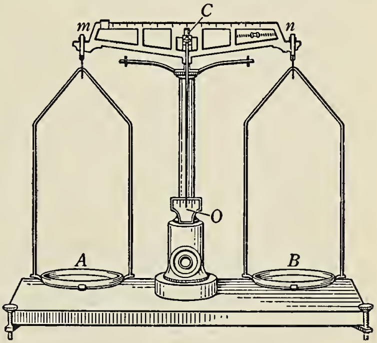


FIG. 5. The simple balance

*[**Significant figures.** Students often waste time and energy in carrying out arithmetical calculations farther than is necessary. In physics work a greater number of figures in the answer does not necessarily mean a greater accuracy. In the student's previous experience the numbers dealt with were exact. In physics, however, almost every number used is one derived from a measurement which always includes some degree of error, depending on the accuracy of the apparatus

* Paragraphs marked with the sign [are to be regarded as supplementary, and may be omitted if the teacher permits.

used and the amount of experience of the user. Such an error limits the accuracy of our calculations.

❲Figures which are meaningful and which are to be kept in any measurement or calculation are called the *significant figures*. They include the figures about which there is no doubt, plus one doubtful figure. Significant figures should not be confused with the number of decimal places; for example, 10.1 and 1.01 both have the same number of significant figures, namely, three.

❲In general it is useless to keep in any answer any more significant figures than there are in the least accurate factor in the calculation or measurement. If the diameter of a sphere could be measured to only three significant figures, 3.14 and not 3.1416 would be used as the value of pi in calculating its volume, and probably not more than three figures need be kept in the answer to give all the accuracy that is possible, owing to the original error in the measurement.

❲The answers to the problems in this book will be sufficiently accurate if no more significant figures are used in the calculations and results than are given in the problem.

❲**The mathematics of physics.** A great deal of the difficulty which students have in beginning physics is due to the fact that they have forgotten the fundamental processes of arithmetic and algebra. The following list of problems, arranged in approximate order of difficulty, was made up from lists, submitted by nine physics teachers, of problems the answers to which were frequently found to contain errors in students' papers. If the student will review these problems at this time and master their difficulties, it may save him considerable trouble later.

PROBLEMS

1. Divide 3,937,000 by 3842.

2. Multiply $\frac{1}{2}$ by $\frac{2}{5}$.

3. Multiply $\frac{3}{4}$ by 8.

4. Multiply 3 by $\frac{3}{4}$.

5. Add $\frac{1}{3}$ and $\frac{2}{5}$.

6. Multiply 13 by 10,000,000.

7. Reduce $\frac{5}{16}$ to a decimal.

8. Add 0.7, .08, 8.2, 9.875, 6.

9. Subtract 7.876 from 10.

10. Multiply 1.0043 by 10,000.

11. Divide 46.34 by 1000.
12. $1.86 \times .2 = ?$
13. Multiply .394 by .2002.
14. What is $\frac{1}{2}$ of .05?
15. .4 divided by $.2 = ?$
16. Divide 4 into 3.6.
17. Divide .073 by 600.
18. Divide .0346 by .00173.
19. Change $\frac{5}{8}$ to a per cent.
20. Change 32 per cent to a decimal.
21. What is 72 per cent of 185?
22. What per cent of 18 is 2?
23. What is the ratio of 10 to 4?
24. Complete this proportion:

$$\frac{6}{4} = \frac{9}{?}.$$

25. Prove that these numbers are approximately in proportion:

$$\frac{12}{26} = \frac{40}{86}.$$

26. $9 \times 10^5 = ?$
27. If $5 = \frac{y}{3}$, solve for y.
28. If $\frac{x}{2} = 4$, solve for x.
29. If $9 = \frac{3}{x}$, solve for x.
30. If $x = \frac{y}{z}$, solve in turn for z and y.
31. If $D = \frac{M}{V}$, solve for V when $D = 7.2$, $M = 1000$.
32. If $t = \pi\sqrt{\frac{l}{g}}$, solve for g.

Summary. **The metric unit of length is the meter, of capacity the liter, and of mass the gram.**

The three fundamental measuring instruments are (1) the meter, to measure *lengths*; (2) the balance, to measure *masses*; (3) the clock, to measure *times*.

1 m = 39.37 in.
1 in. = 2.54 cm
1 km = .62 mi
1 l = 1000 cm^3 = about 1 qt
1 kg = mass of 1 l of water at 4° C. = about 2.2 lb

QUESTIONS AND PROBLEMS

[Remember that answers are valueless unless you give the units in which they are expressed.]

A

1. Write the metric tables for (*a*) capacity; (*b*) mass.

2. (*a*) Find the number of millimeters in 6 km. (*b*) Find the number of inches in 4 mi. (*c*) Which is the easier to do?

3. A new lead pencil is 7 in. long. How many centimeters long is it?

4. With a Vickers-Vimy biplane Captain Alcock and Lieutenant Brown completed, on June 15, 1919, the first nonstop transatlantic flight of 1890 miles from Newfoundland to Ireland in 15 hr 57 min. (*a*) How many miles did they travel per hour? (*b*) How many kilometers per hour?

5. The height of the Empire State Building in New York is 380.4 m. How many feet is it?

6. What must you do (*a*) to find the capacity in liters of a box when its length, breadth, and depth are given in meters? (*b*) to find the capacity in quarts when its dimensions are given in feet?

7. Find the capacity in liters of a box 0.5 m long, 20 cm wide, and 100 mm deep.

8. (*a*) A table was found to be 2 m, 4 dm, 3 cm, and 2.1 mm long. Express this result in centimeters. (*b*) Another table was 2 yd, 1 ft, $3\frac{1}{4}$ in. long. Express this result in inches. (*c*) Which is the easier system to use?

9. Name as many advantages as you can which the metric system has over the English system. Can you think of any disadvantages?

B

1. State some arguments against adopting the metric system for daily use in the United States.

2. The Twentieth Century Limited runs from New York to Chicago (967 mi) in 18 hr. Find its average speed in kilometers per hour.

3. Change to centimeters and draw parallel horizontal lines of the following lengths: (*a*) 0.13 m; (*b*) .00012 km; (*c*) 111 mm; (*d*) 1.03 dm; (*e*) $3\frac{1}{4}$ in.; (*f*) .333 ft; (*g*) 4.75 in.; (*h*) $5\frac{7}{16}$ in.

4. Express your height and weight in the metric system.

5. How many kilograms are there in the 16-pound shot?

6. How many significant figures are there in each of the following numbers? (*a*) 1.07; (*b*) 1.70; (*c*) 0.17; (*d*) .017.

7. The 200-meter run at the Olympic games corresponds to the 220-yard run in our local games. Which is the longer and how much?

Density

Definition of density. Our previous experience has shown us that some things are "heavier" than others. Lead, for instance, is said to be "heavier" than iron, and iron is "heavier" than wood. What we really mean is that equal volumes of the substances have different *masses*. If a unit volume of a substance be taken for comparison, then the mass of that unit volume is called the *density* of the substance.

Thus, for example, in the English system the cubic foot is the unit of volume, and the pound is the unit of mass. Since 1 cubic foot of water is found to weigh 62.4 pounds, we say that in the English system *the density of water is 62.4 pounds per cubic foot* (62.4 lb/ft^3).

In the centimeter-gram-second (C.G.S.) system the cubic centimeter is taken as the unit of volume, and the gram as the unit of mass. Hence we say that in this system the density of water is 1 gram per cubic centimeter (1 g/cm^3), for it will be remembered that the gram was taken as the mass of 1 cubic centimeter of water. Unless otherwise expressly stated, density is now universally understood to signify density in C.G.S. units; that is, *the density of a substance is the mass in grams of 1 cubic centimeter of that substance.*

The following tables contain some useful densities:

Densities of Solids

[In grams per cubic centimeter]

Cork	.2	Glass	2.6	Nickel	8.9
Pine	.5	Zinc	7.1	Silver	10.5
Oak	.8	Tin	7.3	Lead	11.3
Ice	.9	Iron (cast)	7.4	Gold	19.3
Paraffin	.9	Brass	8.5	Tungsten	19.6
Aluminum	2.58	Copper	8.9	Platinum	21.4

Densities of Liquids

[In grams per cubic centimeter]

Ether	.74	Hydrochloric acid	1.27
Gasoline	.75	Carbon bisulfide	1.29
Alcohol	.79	Carbon tetrachloride	1.58
Kerosene	.8	Sulfuric acid	1.84
Glycerin	1.26	Mercury	13.6

Relation between mass, volume, and density. Since the mass of a body is equal to the total number of grams which it contains, and since its volume is the number of cubic centimeters which it occupies, the mass of 1 cubic centimeter is evidently equal to the total mass divided by the volume. Thus, if the mass of 100 cubic centimeters of iron is 740 grams, the density of iron must equal $740 \div 100 = 7.4$ grams per cubic centimeter (7.4 g/cm^3). To express this relation in the form of an equation, let M represent the mass of a body, that is, its total number of grams; V its volume, that is, its total number of cubic centimeters; and D its density, that is, the number of grams in 1 cubic centimeter; then

$$D = \frac{M}{V}. \tag{1}$$

This equation is called a *formula*, and merely states the definition of density in algebraic form. Formulas are used extensively in scientific and industrial work, and the student must be familiar enough with algebraic practice to be able to solve them easily. Solving equation (1) above in turn for M and for V, we have

$$M = DV, \tag{2}$$

and

$$V = \frac{M}{D}. \tag{3}$$

Knowing the volume of a body, and its density (see the table on page 17), we can easily find its mass by substituting these values in formula (2); knowing its mass and density, we can use formula (3) to find its volume.

Distinction between density and specific gravity. The relative heaviness of different materials may also be accu-

rately expressed by use of the term *specific gravity.* The specific gravity of a solid or liquid is the number of times a certain volume of that substance is as heavy as an equal volume of water. Speaking in mathematical terms, it is the ratio of the weight of a body to the weight of an equal volume of water.*

Thus, if a certain piece of iron weighs 7.4 times as much as an equal volume of water, its specific gravity is 7.4. But since the density of water in C.G.S. units is 1 gram per cubic centimeter, the density of iron in that system is 7.4 grams per cubic centimeter (7.4 g/cm^3). It is clear, then, that *density in C.G.S. units is numerically the same as specific gravity.*

Specific gravity is the same in all systems, since it is simply the number obtained by dividing the weight of a body by the weight of an equal volume of water. Density, however, which we have defined as the mass per unit volume, is different in different systems. Thus in the English system the density of iron (which in the metric system is 7.4 grams per cubic centimeter) is 462 pounds per cubic foot (7.4×62.4), since we have found that water weighs 62.4 pounds per cubic foot and that iron weighs 7.4 times as much as an equal volume of water.†

Summary. **The density of a substance is its mass per unit volume. Expressed as a formula,**

$$D = \frac{M}{V}.$$

The specific gravity of a substance is the ratio of the weight of any volume of the substance to the weight of an equal volume of water.

The density of a substance in C. G. S. units is numerically equal to its specific gravity.

The density of a substance expressed in pounds and cubic feet is numerically 62.4 times its specific gravity.

* For the present purpose the terms *weight* and *mass* may be used interchangeably. They are in general numerically equal, although an important distinction between them will be developed on page 99. Weight is, in reality, a *force* rather than a *quantity of matter.*

† Laboratory exercises on length, mass, and density measurements should accompany or follow this chapter. See, for example, Experiments 1, 2, and 3 of *Exercises in Laboratory Physics,* by Millikan, Gale, and Davis.

QUESTIONS AND PROBLEMS

[In substituting numerical values in the formulas for density, do not "mix" units; that is, do not have millimeters and centimeters in the same formula. In general, use C. G. S. units when working with the metric system.]

A

1. A ball of yarn is squeezed into one fourth its original bulk. What effect does this produce (*a*) on its mass? (*b*) on its volume? (*c*) on its density?

2. Which has the greater density, cream or milk?

3. Name three uses made of lead because of its great density, and two uses made of cork because of its small density.

4. Distinguish between the units used in expressing specific gravity and in expressing density.

5. What is the density of water (*a*) in the metric system? (*b*) in the English system?

6. A liter of milk weighs 1032 g. What is (*a*) its density? (*b*) its specific gravity?

7. How many cubic centimeters are there in a block of brass weighing 34 g? (See table of densities, p. 17.)

8. What is the mass of a liter of alcohol? (See table, p. 18.)

9. Find the density in the English system of (*a*) ice; (*b*) copper; (*c*) gold.

10. A housewife, measuring a 100-pound cake of ice left by the iceman, found it to be $18 \times 12 \times 15$ in. Was the ice overweight or underweight, and how much?

B

1. Ten cubic yards of concrete was poured to make a supporting pillar. If the density of the concrete is 180 lb/ft^3, find the mass of the pillar.

2. What is the weight in kilograms of a cube of lead 2 m on an edge?

3. One kilogram of alcohol is poured into a cylindrical vessel and fills it to a depth of 8 cm. Find the cross section of the cylinder.

4. Find the length of a cylindrical lead rod 1 cm in diameter and weighing 1 kg.

5. A bottle filled with mercury weighed 700 g. The bottle empty weighed 20 g. Find the capacity of the bottle in cubic centimeters.

6. A flask holds 2520 g of glycerin when filled. What is the capacity of the flask in liters?

7. A cubical mold is to be made for casting a 50-gram iron weight. What must be its dimensions?

8. If a wooden beam is 30 × 20 × 500 cm and has a mass of 150 kg, (*a*) what is the density of the wood? (*b*) What is its density in the English system?

9. A contractor has to remove 1000 slabs of marble, each 2 in. thick, 12 in. wide, and 6 ft long. How many tons must he remove, marble having a specific gravity of 2.7?

10. A piece of gold weighs 772 g. Find the weight of a piece of lead having a volume equal to that of the gold.

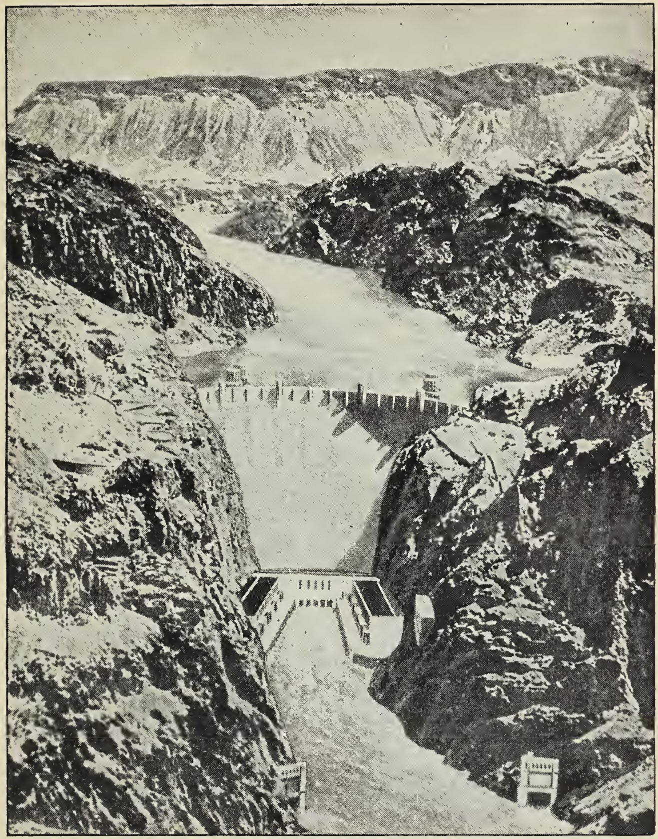
UNIT ONE

The Properties of Fluids

In spite of the fact that the Greeks laid so many of the foundations upon which all later civilizations have been built, the method of experimental science was strangely wanting in their world. They speculated a great deal about nature, but they did not realize the importance of carefully observing and measuring her processes in order to obtain a sure basis for their theories. Nevertheless there was one Greek, Archimedes of Syracuse (287?–212 B.C.), who began to use this method in the study of the properties of liquids, and he is the only Greek whose name is now attached to one of the great laws of modern physics; for the phenomena of flotation and buoyancy in fluids are all adequately explained today by "the principle of Archimedes."

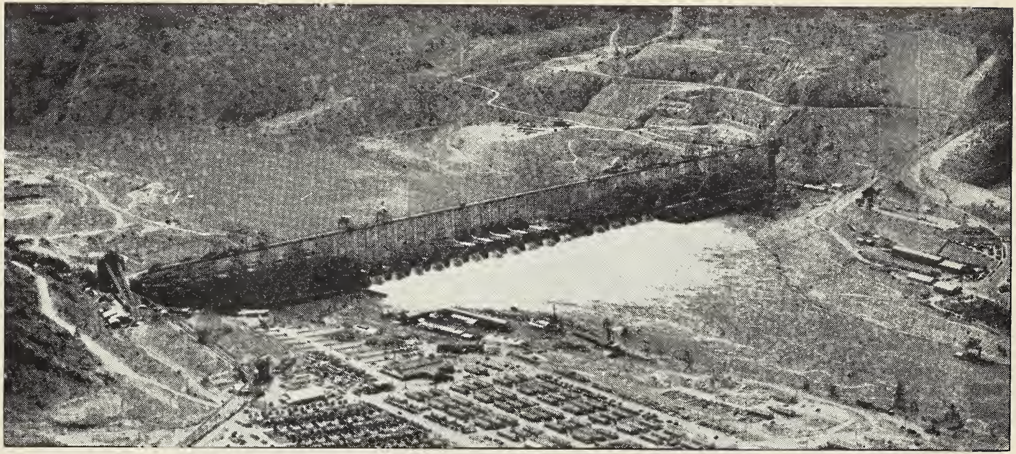
In spite of this conspicuous success it was not until shortly after 1600 A.D. that the foundations were laid for a reasonably complete understanding of the simpler properties, at least, of liquids and gases. It was the brilliant French mathematician, physicist, and philosopher Pascal (1623–1662) who first set forth (1648) the law of the transmission of pressure by fluids, a law that still bears his name and underlies the operation of all modern hydraulic machines. About the same time, too, Torricelli, as a pupil of Galileo, performed his famous experiment (p. 47) that not only established the existence of atmospheric pressure but accurately measured it. This was in 1643. Only a few years later, in Germany, Otto von Guericke invented the air pump

(1650) and made with it his spectacular experiments (see opposite page 51) which added much to our understanding of barometric pressures and other atmospheric phenomena. So that the subject of the properties of liquids and gases was the first portion of physics to come rather fully under the sway of modern physical methods. The way in which all this happened and the application of this knowledge to our daily life and work are what we are to study in the pages of this first unit of physics.



Boulder Dam

This structure, towering 730 feet above bedrock, 45 feet thick at the top, 650 feet thick at the bottom (why the difference?), makes a reservoir 115 miles long of maximum width 8 miles, of area 227 square miles. It holds 30,500,000 acre-feet of water, or enough to flood the entire state of Connecticut to a depth of 10 feet. The powerhouses, capable of developing 1,800,000 horsepower, are shown at the bottom. (Courtesy of the Associated Press)



Grand Coulee Dam

One of the great engineering achievements of our day has been the Grand Coulee Dam (in the state of Washington), which began operation March 24, 1941. This dam was constructed by the Bureau of Reclamation for flood control, electric power, and irrigation. The dam is 550 feet high and piles up a lake 150 miles long. The dam and power plant cost over $200,000,000. The power plant houses about fourteen generators, the estimated capacity of which will be 1,964,000 kilowatts. Grand Coulee will be the world's largest single source of power. As an irrigation project Grand Coulee Dam will irrigate 1,200,000 acres. It is estimated that the project will support a population of 350,000 on farms and in towns. (Courtesy of *Life* Magazine)

CHAPTER II

Pressure in Liquids

Liquid Pressure beneath a Free Surface

Definition of force. In order to lift a kilogram of mass we must exert an upward push or pull. The greater the mass, the greater the force which we must exert. The force is commonly taken as numerically equal to the mass lifted; that is, to lift a kilogram of mass requires a kilogram of force. This is called the *weight measure* of a force. *A push or pull which is equal to that required to support a gram of mass is called a gram of force.* Thus 5 grams of force are needed to lift a new five-cent piece.

Force beneath the surface of a liquid. When a piece of cork is released below the surface of water, it is immediately forced up to the surface, where it floats. An ocean liner, although constructed of steel and weighing thousands of tons, is supported by the upward force of the water against the bottom of the ship. Street water mains which are far below the level of the water in the reservoir not infrequently burst from the force of the water.

To investigate the nature of the forces beneath the free surface of a liquid, we will use a pressure gauge of the form shown in Fig. 6. If the rubber diaphragm which is stretched across the mouth of a thistle tube *A* is pressed in lightly with the finger, the top *B* of the column of colored water will be observed to move upward in the tube *T*, but it will return to its first position as soon as the finger is removed. If the pressure of the finger is increased, the column will rise a greater distance than before. We may therefore take the amount of motion of the column as a measure of the force acting on the diaphragm.

Now push *A* down first 10 cm, then 20 cm, then 30 cm below the surface of the water (Fig. 6). The motion of the water level *B* will

show that as the depth increases, the upward force on the diaphragm increases in the same proportion.

Careful measurements made in the laboratory will show that *the force is directly proportional to the depth.**

This law of physics may also be stated mathematically in the form of a literal (letter) proportion. Let F_1 represent the force exerted on a surface whose depth is h_1, and F_2 represent the new force when the depth is changed to h_2. Then

$$\frac{F_1}{F_2} = \frac{h_1}{h_2}. \tag{1}$$

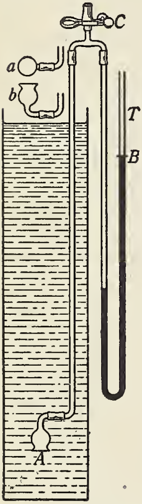


FIG. 6. Gauge for measuring liquid pressure

Push the diaphragm A (Fig. 6) down to some convenient depth (for example, 10 cm) and note the position of the water level, B, by a little rubber ring cut from a piece of tubing. Then turn the diaphragm sidewise so that its plane is vertical (see a, Fig. 6), and adjust its position until its center is exactly 10 cm beneath the surface; that is, until the *average* depth of the diaphragm is the same as before. The position of the water level will show that the force is exactly the same as before.

Turn the diaphragm to the position b, so that the gauge measures the *downward* force at a depth of 10 cm. The index will show that this force is again the same.

We conclude, therefore, that *at a given depth a liquid presses up and down and sideways on a given surface with exactly the same force.*

This statement seems logical, since we know that water in a glass vessel is seen to be ordinarily at rest. If the forces at any point were not the same in all directions, the water at that point would tend to move in the direction of the greater force. Since it does not, we conclude that the forces at that point are equal in all directions.

* It is recommended that quantitative laboratory work on the law of depths and on the use of manometers accompany this discussion. See, for example, Experiment 4 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

Magnitude of the force. If a vessel like that shown in Fig. 7 is filled with a liquid, the force against the bottom is obviously equal to the weight of the column of liquid resting upon the bottom. Thus, if F represents this force in grams, A the area in square centimeters, h the depth in centimeters, and d the density in grams per cubic centimeter, we shall have

$$F = Ahd, \tag{2}$$

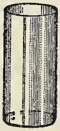


FIG. 7

since Ah represents the number of cubic centimeters of liquid, and d the weight of *one* cubic centimeter. Similarly the force will be computed in pounds if the units used are square feet, feet, and pounds per cubic foot. Since, as was shown by the experiment of the preceding section, the force on a given area is the same in all directions at a given depth, we have the following general rule:

The force which a liquid exerts against any surface is equal to the area of the surface times its average depth times the density of the liquid.

It is important to bear in mind that "average depth," h, means the vertical distance from the level of the free surface to the center of the area in question (Fig. 8).

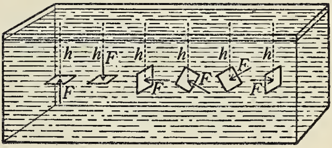


FIG. 8. The average depth h is the distance from the free surface to the center of the area

Pressure in liquids. Thus far attention has been confined to the total force exerted by a liquid against the *whole* of a given surface. The same force applied to different areas, however, will produce different results. When we want to consider the *intensity* of the force at any particular point, as when the whole force of a man's weight is concentrated on the narrow runners of his skates, we speak of the *pressure* rather than the force. *Pressure is defined as the force per unit area.* To illustrate, if we have 1000 grams of water in a box having a bottom area of 100 square centimeters, the total

force on the bottom (due to the weight of the water) will be 1000 grams, while the pressure (force on *one* square centimeter) will be $\frac{1000}{100} = 10$ grams per square centimeter (10 g/cm^2).

Since $F = Ahd$, and since by definition the pressure p is equal to the force per unit area, we have

$$p = \frac{F}{A} = \frac{Ahd}{A} = hd. \tag{3}$$

Therefore *the pressure at a depth of h centimeters below the surface of a liquid of density d is hd grams per square centimeter.*

If the height is given in feet and the density in pounds per cubic foot, then the product *hd* gives the pressure in pounds per square foot. Since there are 144 square inches in 1 square foot, dividing by 144 gives the result in pounds per square inch.

Levels of liquids in connecting vessels. It is a familiar fact that when water is poured into a teapot it stands at exactly the same level in the spout as in the body of the teapot; or if it is poured into a number of connected vessels like those shown in Fig. 9, the surfaces of the liquid in the various vessels lie in the same horizontal plane.

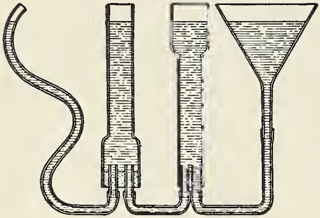


FIG. 9. Water level in communicating vessels

Use is made of this fact to check the water level in a steam boiler, in order that it may not run dry and explode. A small vertical glass tube, called a gauge glass (Fig. 10), is mounted on the side of the boiler, and connected at the top and bottom to the boiler by two horizontal pipes. The level of the water in the gauge glass is the same as that in the main boiler, and it needs only a glance at the glass to determine whether the boiler needs refilling.

Fig. 11 shows why water seeks its own level. The pressure at *c* was shown by the experiment on page 26 to be equal to the density of the liquid times the depth *cg*. The pressure at *o* in the opposite direction must be equal to that at *c*, since the liquid does not tend to move in either direction. Hence the pressure at *o* must be *cg* (= *ks*) times the density; that is, the vertical depth beneath the free surface times the density.

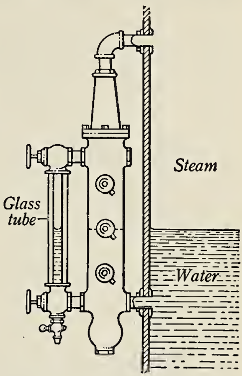


FIG. 10. Water gauge on a boiler

If water is poured in at *s* so that the height *ks* is increased, the pressure to the left at *o* becomes greater than the pressure to the right at *c*, and a flow of water takes place to the left until the heights are again equal.

It follows from these observations on the level of water in connected vessels that *the pressure beneath the surface of a liquid depends simply on the vertical depth beneath the free surface, and not at all on the size or shape of the vessel.*

[**Deep-sea pressures.** The rapidity with which pressure increases with the depth of water is of great importance in deep-sea diving operations when sunken vessels are salvaged. Workers in caissons and divers carrying on salvage work apparently stand great pressure without serious difficulty. Within recent years the depth at which successful diving operations have been carried out (see opposite page 71) has been extended to 300 feet, where the pressure is 130 pounds per square inch. The danger comes with returning too rapidly to atmospheric pressure, and it is necessary to exercise caution in order to avoid "the bends," or caisson disease.

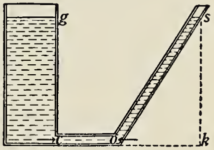


FIG. 11. Why water seeks its level

In a hollow steel sphere called a bathysphere men have recently descended more than 3000 feet in the ocean to study the marine life there. Oxygen for breathing was supplied by tanks. Although the outside pressure was 1300 pounds per square inch, the pressure inside was normal. Millions of people saw this apparatus exhibited at the Century of Progress Exposition in Chicago.

Summary. **A force is a push or a pull. A gram of force is the push or pull which is required to support 1 gram of mass at the earth's surface.**

Force on a submerged surface is measured by the formula

$$F = Ahd.$$

Pressure is force per unit area $= \frac{F}{A}$.

The pressure at a given point within a liquid is the same in all directions.

Pressure, measured in grams per square centimeter, is the vertical depth h below the surface times the density d of the liquid; that is, $p = hd$.

All parts of the free surface of a liquid in the same vessel or in connecting vessels lie in the same horizontal plane.

QUESTIONS AND PROBLEMS

A

1. Upon what factors does the force on a submerged surface depend?

2. Upon what factors does the pressure on a submerged surface depend?

3. Find the force on a horizontal surface 2 ft by 4 ft submerged in water (*a*) to a depth of 2 ft; (*b*) to a depth of 4 ft.

4. Find the pressures on the surfaces of the preceding problem.

5. Find the force on a horizontal surface 10 cm square submerged in water to a depth of (*a*) 10 cm; (*b*) 100 cm; (*c*) 100 m.

6. Find the pressures on the surfaces of the preceding problem.

7. A standpipe 100 ft high is filled with water. Determine the pressure at the bottom in pounds per square foot and in pounds per square inch.

8. A hole 5 cm square is made in a ship's bottom 7 m below the water line. What force in kilograms is required to hold a board above the hole?

B

1. A fish swims horizontally across a lake (Fig. 12), as indicated by the dotted line, first in deep water, then in shallow water, and finally under an overhanging rock. How does the force of the water upon the fish compare in the three places? Explain fully.

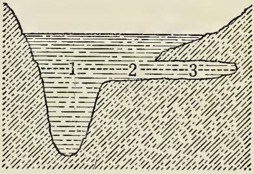


FIG. 12

2. A man weighing 180 lb is walking on snow. The soles of his shoes are each 30 in.^{2} in area. When his entire weight rests on one foot, (*a*) what *force* does his foot exert on the snow? (*b*) What *pressure* does it exert? If he uses snowshoes, each having an area of 300 in.^{2}, (*c*) what is the pressure of one snowshoe when it supports his entire weight? (*d*) What is its force? (*e*) Why do snowshoes sink less in snow than ordinary shoes?

3. A skater weighs 140 lb. If the skate area in contact with the ice is $\frac{1}{50}$ in.^{2}, what pressure in pounds per square inch will be exerted on the ice?

4. If the point of a lead pencil has an area of $\frac{1}{500}$ in.^{2}, and you push it against a piece of paper with a force of 2 lb, how great is the pressure?

5. Kerosene has a density .8 that of water (1 ft^3 of water = 62.4 lb). Find the pressure of the kerosene per square foot and per square inch on the bottom of an oil tank filled to a depth of 30 ft.

6. If the water pressure in the city mains is 70 lb/in.^{2}, how high above the town is the top of the water in the standpipe?

7. A swimming pool 50 ft square is filled with water to a depth of 5 ft. Find the force of the water (*a*) on the bottom; (*b*) on a side.

8. (*a*) Find the total ~~force against the gate of a lock~~ if its width is 60 ft and the depth of the water 20 ft. (*b*) Will it have to be made stronger if it holds back a lake than if it holds back a small pond?

9. A U-tube having a cross section of 1 cm^2 is filled to a certain level with mercury (density 13.6 g/cm^3). Then 20 cm^3 of water is poured into one side. What is now the difference in level between the top of the water on one side and the top of the mercury on the other?

10. If the areas of the surfaces *AB* in Fig. 13, (*a*) and (*b*), are the same, and if water is poured into each vessel at *D* till it stands at the same height above *AB*, how will the downward force on *AB* in Fig. 13 (*b*) compare with that in Fig. 13 (*a*)? Test your answer, if possible, by making *AB* a piece of cardboard and pouring water in at *D*, in each case, until the cardboard is forced off.

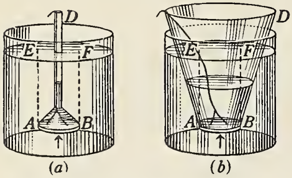


FIG. 13. Illustration of hydrostatic paradox

11. A swimming pool has a sloping bottom 75 ft long and 30 ft wide. The water is 9 ft deep at one end and 4 ft deep at the other. Find the total force (*a*) on the bottom; (*b*) on the end which measures 9 ft by 30 ft.

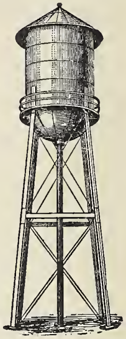


FIG. 14. A water reservoir

12. Deep-sea fish have been caught in nets at a depth of a mile. How many pounds pressure are there to the square inch at this depth? (Specific gravity of sea water = 1.026.)

13. If the pressure at a tap on the first floor reads 80 lb/in.^{2}, and at a tap two floors above, 68 lb, what is the difference in feet between the levels of the two taps?

14. Forty years ago standpipes were generally straight cylinders. Today they are more commonly of the form shown in Fig. 14. What are the advantages of each form?

15. If the vessel which is shown in Fig. 15 (*a*) has a base of 200 cm^2 and if the water stands 100 cm deep, what is the total force on the bottom?

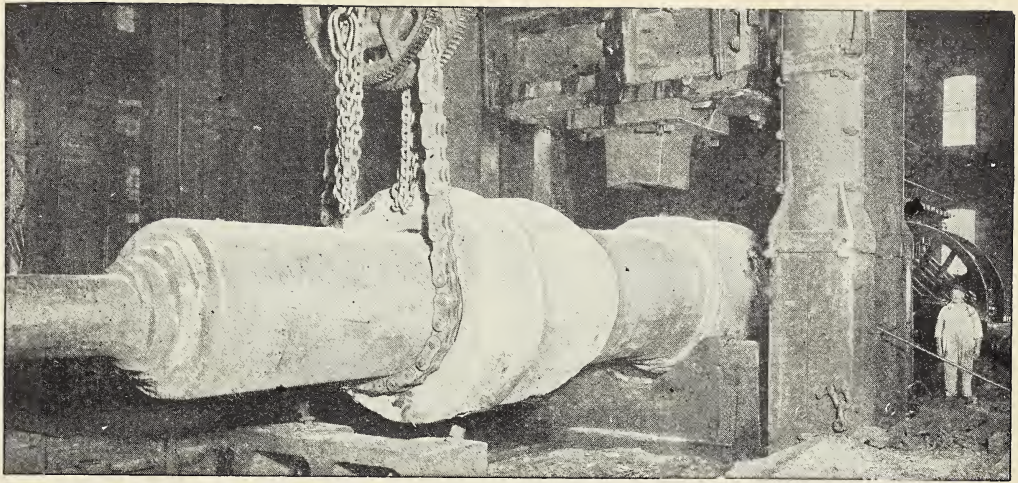
Pascal's Law

Transmission of pressure by liquids. You may have sat in a barber's or dentist's chair and watched the operator, with a few easy strokes of a lever, lift you into a convenient working position. How did he do it so easily?

From the fact that pressure within a free liquid depends simply upon the depth and density of the liquid it is possible

Pneumatic Appliances

The grease gun, illustrated above, is only one of numerous applications of fluids under pressure, in this case air instead of water or oil. Pneumatic tools include rock drills, used in road construction, in mines, and in quarries; blow guns, for cleaning buildings; and airbrushes, for applying paint, varnish, and enamel. Pneumatic hammers for driving rivets or for chipping metal or for removing paint and rust are commonly used. Pneumatic tools are standard equipment in any machine shop. All these tools work on the same general principle; namely, compressed air enters a cylinder through a valve in the handle controlled by the operator by means of a trigger, as here shown. (Courtesy of New York *Journal-American*)

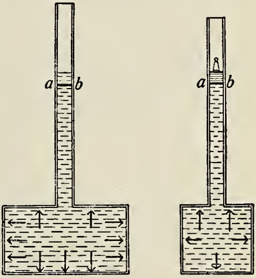


A Hydraulic Press

This picture of a hydraulic press was taken when the press was making a huge hollow forging of steel 52 inches inside diameter, 62 inches outside diameter, and 44 feet long. A mass of red-hot steel weighing 100 tons is being squeezed by the enormous forces of the press out over a solid steel mandrel weighing $87\frac{1}{2}$ tons. The press exerts between its jaws a force of 14,000 tons. This tremendous force is transmitted to the jaws from two cylinders each $50\frac{1}{2}$ inches in diameter and each sustaining a hydraulic pressure of 7000 pounds per square inch. When the huge hollow forgings are completed they are used as reaction chambers for the cracking of gasoline. (Courtesy of the Bethlehem Steel Company)

to deduce a very surprising conclusion, which was first stated by the famous French scientist, mathematician, and philosopher Pascal.

Let us imagine a vessel of the shape shown in Fig. 15 (*a*) to be filled with water up to the level *ab*. For simplicity let the upper portion be assumed to be 1 square centimeter in cross section. Since the density of water is 1, the force with which it presses against any square centimeter of the interior surface which is h centimeters beneath the level *ab* is h grams. Now let 1 gram of water (that is, 1 cubic centimeter) be poured into the tube. If a given square centimeter of surface was before h centimeters beneath the level of the water in the tube, it is now $h + 1$ centimeters beneath this level. Therefore the new pressure which the water exerts against it is $h + 1$ grams; that is, applying 1 gram of force to the square centimeter of surface *ab* has added 1 gram to the force exerted by the liquid against each square centimeter of the interior of the vessel. Obviously it can make no difference whether the pressure which was applied to the surface *ab* was due to a weight of water, or to a piston carrying a load, as in Fig. 15 (*b*), or to any other cause whatever. We therefore arrive at Pascal's conclusion, namely, that *pressure applied anywhere to a body of confined liquid is transmitted undiminished to every portion of the surface of the containing vessel.*



(*a*) (*b*)

FIG. 15. Proof of Pascal's law

Multiplication of force by the transmission of pressure by liquids. Pascal himself pointed out that with the aid of the principle stated above we ought to be able to transform a very small force into one of unlimited magnitude. Thus, if the area of the cross section of the cylinder *ab* (Fig. 16) is 1 square centimeter, and that of the cylinder *AB* is 1000 square centimeters, a force of 1 kilogram applied to *ab* would

be transmitted by the liquid so as to act with a force of 1 kilogram on each square centimeter of the surface AB. Hence the total upward force exerted against the piston AB by the 1 kilogram applied at ab would be 1000 kilograms. Pascal's own words are as follows: "A vessel full of water is a new principle in mechanics, and a new machine for the multiplication of force to any required extent, since one man will by this means be able to move any given weight."

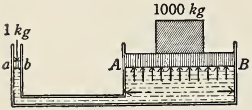


FIG. 16. Multiplication of force by transmission of pressure

Among the practical applications of Pascal's law are automobile lifts for greasing stations, barbers' and dentists' chairs, hydraulic presses, hydraulic automobile brakes, and hydraulic elevators for buildings.

Hydraulic press. An experimental proof of the correctness of the conclusions of the preceding paragraph is furnished by the hydraulic press, an instrument now in common use for baling paper, cotton, etc. and for punching holes through iron plates, testing the strength of iron beams, extracting oil from seeds, making dies, embossing metal, etc. Hydraulic presses of great power have been designed for use in steel works to replace huge steam hammers (see opposite page 33). Compressions of 14,000 tons or more are thus obtained. Much cold steel, as well as hot, is now pressed instead of hammered.

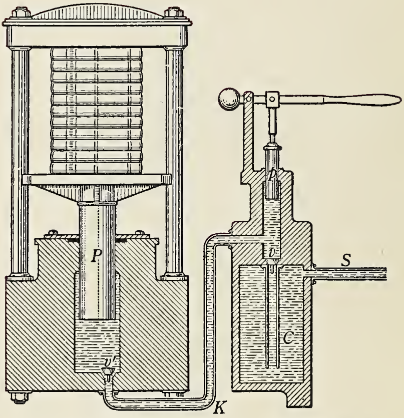
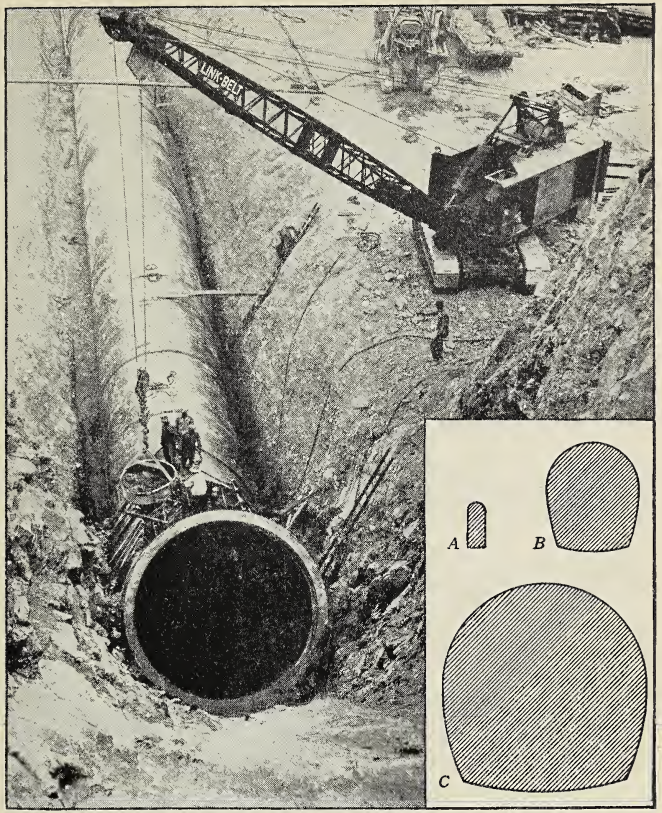


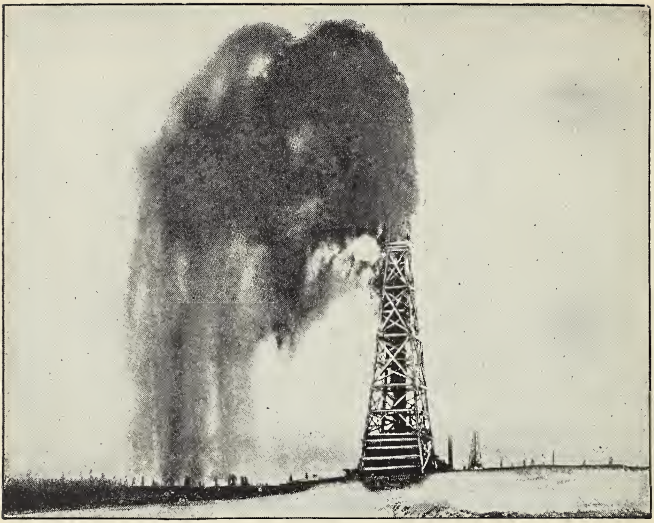
FIG. 17. Diagram of a hydraulic press

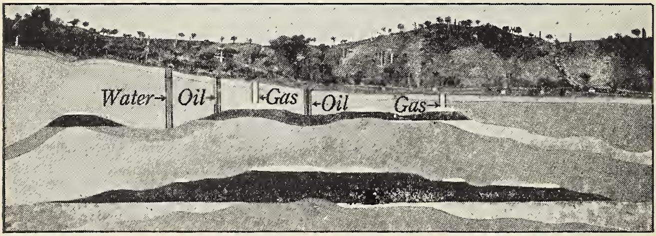
When the small piston p of the press shown in Fig. 17 is raised, water or oil from the cistern C enters the piston chamber through the



Aqueducts

Section of the great 300-mile Colorado River aqueduct for transporting a billion gallons of water daily, over a total lift of 1605 feet, to Southern California. It consists of 107 miles of tunnels 16 feet in diameter, 65 miles of concrete-lined canals, 80 miles of concrete conduit, and 40 miles of concrete or steel pressure pipe. Cost, $220,000,000. The inset shows the relative capacities of (*A*) the ancient Hadrian aqueduct (4 cubic feet per second); (*B*) the new Athens aqueduct, just built (39 cubic feet per second); (*C*) the Colorado River aqueduct (1600 cubic feet per second)





A Spouting Oil Well

Gas and oil are found in porous rocks having a nonporous covering; for example, the porous rock may be limestone or sandstone, and the nonporous covering may be shale. Frequently water is found below, the oil and gas being on top. The pressure of the gas sometimes exceeds 1000 pounds to the square inch; hence, if a boring is made into the layer of water or oil, the boring tools and derrick may be blown high in the air by the rushing water or oil. When the pressure of the expanding gas falls too low to force the oil from the boring, pumping must be resorted to. Natural gas is piped a thousand miles from Texas to Chicago, where millions of cubic feet of it are burned daily.

We have here an illustration of Pascal's law on a grand scale in nature

on the top of this block is equal to the weight of the column of liquid C'. It is clear, then, that the upward force must exceed the downward force by the weight of the liquid whose volume is equal to that of the block. Archimedes' principle may be stated thus:

The buoyant force exerted by a liquid is exactly equal to the weight of the displaced liquid.

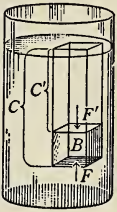


FIG. 21. Proof that an immersed body is buoyed up by a force equal to the weight of the displaced liquid

The reasoning is exactly the same, no matter what may be the kind of liquid in which the body is immersed, nor how far the body may be beneath the surface. Further, if the body weighs more than the liquid which it displaces, it must sink; for it is urged down with the force of its own weight, and up with the lesser force of the weight of the displaced liquid. But if it weighs less than the displaced liquid, then the upward force due to the displaced liquid is greater than its own weight, and consequently it must rise to the surface. When it reaches the surface, the downward force upon the top of the block, due to the liquid, becomes zero. The body must, however, continue to rise until the upward force on its bottom is equal to its own weight. But this upward force is always equal to the weight of the displaced liquid, that is, to the weight of the column of liquid *mbcn* (Fig. 22). Hence

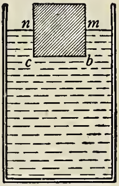


FIG. 22. Proof that a body which floats is buoyed up by a force equal to the weight of the displaced liquid

A floating body displaces its own weight of the liquid in which it floats.

This statement is embraced in the statement of Archimedes' principle, for a body which floats has lost its whole weight. (See opposite page 40.) (Remember that this loss is an apparent one, not real. The attraction of the earth for the floating body is still the same.)

To test our reasoning for this case, place an overflow can (Fig. 23) on a trip scale, fill it with water, and carefully balance it. Now float a block of wood in the can. When the overflow of water ceases, the scales again balance. What do you conclude?

FIG. 23. An overflow can

Specific gravity of a heavy solid. The specific gravity of a body is by definition the ratio of its weight to the weight of an equal volume of water (p. 19). Since a submerged body displaces a volume of water equal to its own volume, however irregular it may be,

$$\text{Specific gravity of body} = \frac{\text{weight of body}}{\text{weight of water displaced}}.$$

Making application of Archimedes' principle, we have

$$\text{Specific gravity of body} = \frac{\text{weight of body}}{\text{buoyancy (or loss of weight in water)}}.$$

Specific gravity of a solid lighter than water. If the body is too light to sink of itself, we may still obtain the weight of the equal volume of water by forcing it beneath the surface by means of a sinker. Thus, suppose w_1 represents the weight on the right pan of the balance when the body is in air and the sinker is under water, as in Fig. 24, and w_2 the weight on the right pan when both body and sinker are under water. Then $w_1 - w_2$ is obviously the buoyant effect of the water upon the body alone (or its loss of weight in water) and is therefore equal to the weight of the displaced water.

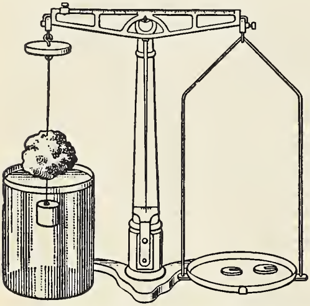
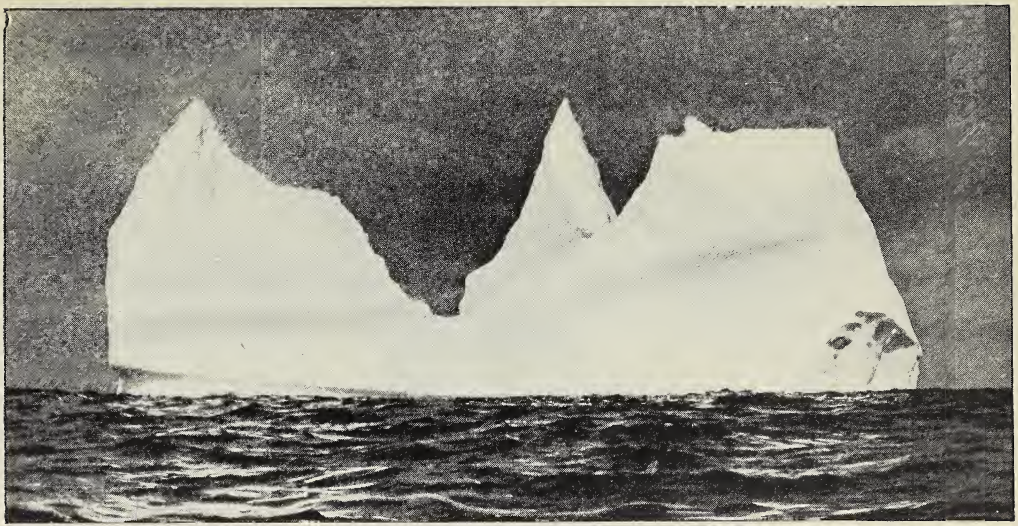


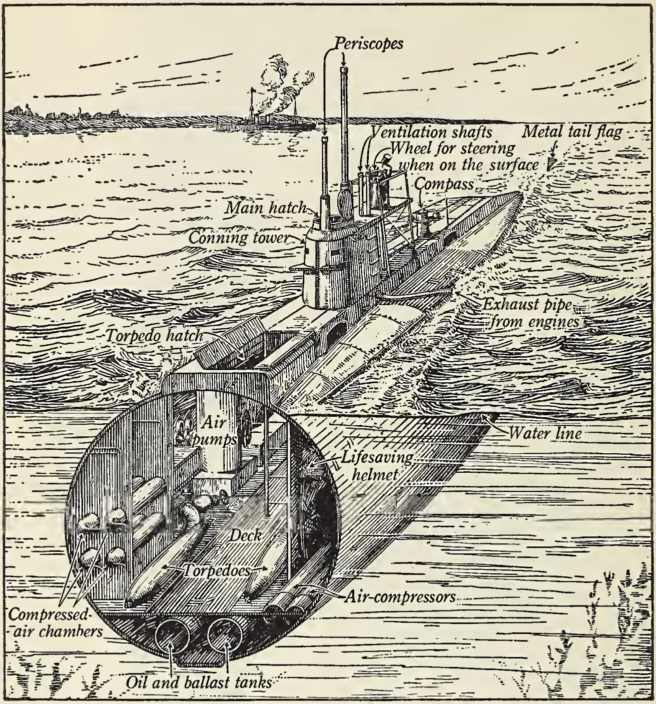
FIG. 24. Method of finding specific gravity of a light solid

Specific gravity of liquids by the hydrometer method. The hydrometer was invented by the Greeks about sixteen hundred years ago. The commercial hydrometer that is now commonly used for testing the specific gravity of alcohol,



An Iceberg

This huge iceberg was formed by the movement into the sea of the great glacial icecap of Greenland. Glacier ice, being somewhat porous, has a density less than that of solid ice. About six sevenths of the mass of an iceberg is below the level of the sea, the bottom in some cases being at least 1500 feet below the surface. Some icebergs contain enough ice to cover a square mile to a depth of 500 feet. Icebergs are dangerous to shipping at night and in fogs



The Details of a Submarine

The submarine, one of the newest of marine inventions, is a simple application of the principle of Archimedes — one of the oldest principles of physics. In order to submerge, the submarine allows water to enter her ballast tanks until the total weight of the boat and contents becomes nearly as great as that of the water she is able to displace. The boat is then almost submerged. When she is under headway in this condition, a proper use of the horizontal, or diving, rudders sends her beneath the surface, or, if submerged, brings her to the surface, so that she can scan the horizon with her periscope. The whole operation takes but a few seconds. When the submarine wishes to come to the surface for recharging her batteries or for other purposes, she blows compressed air into her ballast tanks, thus driving the water out of them. Submarines are propelled on the surface by Diesel oil engines; underneath the surface, by storage batteries and electric motors

milk, acids, sugar solutions, etc. is of the form shown in Fig. 25. The stem is calibrated by trial so that the specific gravity of any liquid may be read upon it directly. The principle involved is that a floating body sinks until it has displaced its own weight. In heavier liquids it floats higher, since it does not have to sink as deeply to displace its own weight of the liquid. The higher specific gravities would therefore be at the bottom of the scale, and the lower values at the top. By making the stem very slender the sensitiveness of the instrument may be made very great. Why?

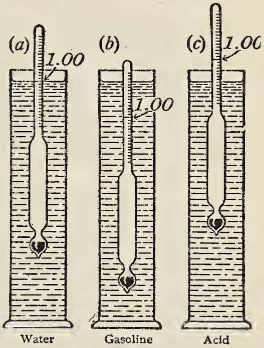


FIG. 25. Constant-weight hydrometer

The hydrometer is of value to the motorist. In one form he uses it to test the state of charge or discharge of his storage battery (see Fig. 328); in another form he tests in winter the antifreeze mixture in his radiator. In this form the scale, instead of being marked off in terms of the specific gravity of the liquid, is calibrated directly in the corresponding freezing points of the mixture. Different scales are needed for the various types of freezing mixtures. The hydrometer is placed in a glass tube, called a syringe, into which the liquid to be tested is drawn up by squeezing and then releasing a rubber bulb at the top.

Specific gravity of liquids by "loss of weight" method. If any suitable solid be weighed first in air, then in water, and then in a liquid of unknown specific gravity, by the principle of Archimedes its loss of weight in the liquid is equal to the weight of the liquid displaced, and its loss in water is equal to the weight of the water displaced. If we divide the loss of weight in the liquid by the loss of weight in water, we are dividing the weight of a given volume of liquid by the weight of an equal volume of water. Therefore,

*To find the specific gravity of a liquid, divide the loss of weight of some solid in it by the loss of weight of the same body in water.**

Summary. Archimedes' principle. The buoyant force exerted by a liquid is equal to the weight of the displaced liquid.

$$\text{Specific gravity of a heavy solid} = \frac{\text{weight of solid}}{\text{loss of weight in water}}.$$

Specific gravity of a light solid (sinker method)

$$= \frac{\text{weight of solid}}{(\text{weight of solid in air} + \text{sinker in water}) - \text{weight of both in water}}.$$

Specific gravity of a liquid ("loss of weight" or "bulb" method)

$$= \frac{\text{loss of weight of solid in liquid}}{\text{loss of weight of solid in water}}.$$

QUESTIONS AND PROBLEMS

[In solving problems involving formulas, first write the formula, then indicate all work immediately underneath it. (See bottom of page 48.) Make all possible cancellations before solving.]

A

1. A newly laid egg is said to sink in a glass of water in which a teaspoon of salt has been dissolved. After four to six weeks it will float in plain water. (*a*) What change has taken place in its specific gravity? (*b*) Could you use this test to estimate the freshness of the egg?

2. Explain by reference to the upward and downward forces of water and the weight of the body (*a*) why a piece of cork when released under water rises; (*b*) why a piece of iron or stone sinks.

3. Does the weight apparently lost by a submerged body depend upon its volume or its weight? Explain.

4. A piece of lead on one side of a trip scale balances a piece of aluminum on the other side. If the trip scale is now immersed in a tub of water, which metal will appear to be the heavier? Explain.

5. Let a vessel of water, together with an object heavier than water, be counterpoised as in Fig. 26 (position *a*). Now if the

* Laboratory experiments on the determination of the densities of solids and liquids should follow or accompany the discussion of this chapter. See, for example, Experiments 6 and 7 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

object be placed inside the vessel of water (position *b*), will the scales remain balanced? Predict the result, and then try the experiment.

6. A brick lost 1 lb when submerged 1 ft deep. How much would it lose if suspended 3 ft deep?

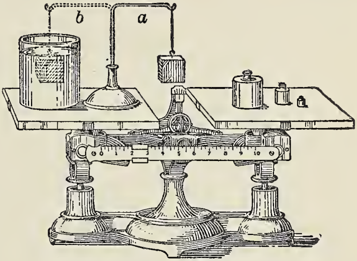


FIG. 26

7. Steel is three times as dense as aluminum. When equal volumes of the two are submerged in water, how do their apparent losses of weight compare?

8. A boy who can just float weighs 124.8 lb. What is his volume?

9. An empty milk bottle weighed 1 lb $10\frac{1}{2}$ oz; filled with water, it weighed 3 lb $11\frac{1}{2}$ oz; filled with milk, it weighed 3 lb $12\frac{1}{2}$ oz. Find the specific gravity of this specimen of milk.

10. A graduated glass cylinder contains 190 cm^3 of water. An egg weighing 40 g is dropped into the glass; it sinks to the bottom and raises the water to the 225-cubic-centimeter mark. Find the density of the egg.

B

1. A body loses 25 g in water, 23 g in oil, and 20 g in alcohol. Find the specific gravity (*a*) of the oil and (*b*) of the alcohol.

2. A platinum ball weighs 330 g in air, 315 g in water, and 303 g in sulfuric acid. Find (*a*) the volume of the ball, (*b*) the specific gravity of the platinum, and (*c*) the specific gravity of the acid.

3. A cubic foot of stone weighed 110 lb in water. Find (*a*) its density in pounds per cubic foot; (*b*) its specific gravity.

4. A piece of sandstone having a specific gravity of 2.6 weighs 480 g in water. Find its weight in air.

5. A cube of iron 10 cm on a side weighs 7500 g. What will it weigh in alcohol of density 0.82 g/cm^3?

6. A stone has a weight of 300 g and a volume of 90 cm^3. What is its apparent weight when submerged in kerosene having a specific gravity of 0.79?

7. A block of wood 15 cm by 10 cm by 4 cm floats in water with 1 cm in the air. Find (*a*) the weight of the wood and (*b*) its specific gravity.

8. The hull of a modern battleship is made almost entirely of steel, its walls being of steel plates from 6 to 18 in. thick. Explain how it can float.

9. Will a boat rise or sink deeper in the water as it passes from a river to the ocean?

10. Do the larger numbers appear on hydrometers toward the bottom of the stem or toward the top? Explain.

11. A barge 30 ft by 15 ft sank 4 in. when an elephant was taken aboard. What was the elephant's weight?

12. What fraction of the volume of a block of wood will float above water (*a*) if its specific gravity is .5? (*b*) if its specific gravity is .6? (*c*) if its specific gravity is .9? (*d*) State in general what fraction of the volume of a floating body is under water.

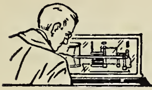
13. A block of wood 10 in. high sinks 6 in. in water. Find the specific gravity of the wood.

14. What must be the specific gravity of a liquid in which a body having a specific gravity of 6.8 will float with half its volume submerged?

15. A piece of paraffin weighed 178 g in air, and a sinker weighed 30 g in water. Both together weighed 8 g in water. Find the specific gravity of the paraffin.

16. If in Problem 15 half the paraffin be cut away, the weight of the remainder in water, with the sinker attached, is 19 g instead of 8 g. Prove that this is true and explain the apparent increase in weight.

17. Suppose Hiero's crown weighed 1070 g and lost 60 g weight in water. Find (*a*) how many cubic centimeters of gold there were in the crown; (*b*) how many cubic centimeters of silver; (*c*) how many grams of gold; (*d*) how many grams of silver. (See table of densities, p. 17.)



CHAPTER III

Pressure in Air

Barometric Phenomena

The weight of air. Ordinarily we are not conscious of the air about us, if it is not in motion. It appears to have no weight, and to offer no resistance to bodies which pass through it, at least at ordinary speeds. If, however, a bulb is balanced as in Fig. 27, and then removed and filled with air under pressure by a few strokes of a bicycle pump, it will be found, when placed on the balance again, to be heavier than it was before. On the other hand, if the bulb is connected with an air pump and exhausted, it will be found to have lost weight. Evidently, then, air can be put into and taken out of a vessel, weighed, and handled, just like a liquid or a solid.

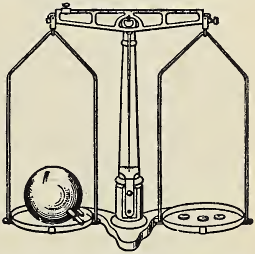


FIG. 27. Proof that air has weight

We often say that bodies are "as light as air"; yet careful measurement shows that it takes but 12 cubic feet of air to weigh a pound. Therefore a single large room contains more air than a man can lift. Thus the air in a room 60 feet by 30 feet by 15 feet weighs more than a ton. The exact density of air at the freezing temperature and under normal atmospheric pressure is .001293 gram per cubic centimeter. A given volume of air therefore weighs $\frac{1}{773}$ as much as an equal volume of water.

Proof that air exerts pressure. We live at the bottom of a sea of air. Since air has weight and reaches above the earth

to an indefinite height, it can easily be seen that air, like a liquid, exerts a considerable force against any surface immersed in it. The following experiments prove this in a very convincing manner:

Stretch a thin piece of rubber over a glass vessel (called a bell jar), as in Fig. 28. As air is exhausted from beneath the rubber, it will be pushed in more and more until it finally bursts.

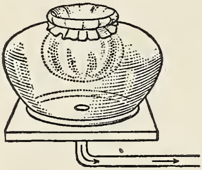


FIG. 28. Rubber membrane stretched by the weight of air

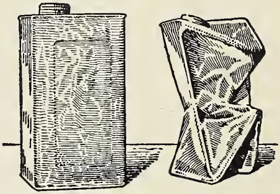


FIG. 29. Gallon can crushed by atmospheric pressure

Cover the bottom of a tin can with an inch of water. Boil the water until the escaping steam shows that all the air has been replaced with steam. Promptly cork the can and pour cold water over it. Since 1600 cm^3 of steam condenses to form 1 cm^3 of water, a partial vacuum is left in the can, and the weight of the air outside crushes it (Fig. 29).

Cause of the rise of liquids in exhausted tubes. If the lower end of a long tube is dipped into water and the air exhausted from the upper end, water will rise in the tube. We prove the truth of this statement every time we draw lemonade through a straw. The old Greeks and Romans explained such phenomena by saying that "nature abhors a vacuum" (a space in which there is no air), and this explanation was still in vogue in Galileo's time. But in 1640 the duke of Tuscany had a deep well dug near Florence, and found to his surprise that no water pump that could be obtained would raise the water higher than about 32 feet above the level in the well. When he applied to the aged Galileo (see opposite page 106) for an explanation, the latter replied that evidently "nature's abhorrence of a vacuum does

not extend beyond 32 feet." It is quite probable that Galileo suspected that the pressure of the air was responsible for the phenomenon, for he had himself already proved that air has weight; and, furthermore, he at once devised another experiment to test, as he said, the "power of a vacuum." He died in 1642, before the experiment was performed, but he had suggested to his pupil Torricelli that he continue the investigation.

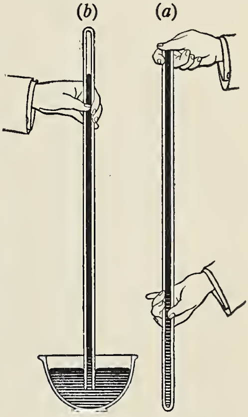


FIG. 30. Torricelli's experiment

Torricelli's experiment. Torricelli argued that if water would rise 32 feet, then mercury, which is about 13 times as heavy as water, ought to rise but $\frac{1}{13}$ as high. To test this inference he performed in 1643 this famous experiment:

Fill a tube about 3 ft long, sealed at one end, completely with mercury, as in Fig. 30 (*a*), close with the thumb, and invert; then immerse the bottom in a dish of mercury, as in Fig. 30 (*b*). When the thumb is removed from the bottom of the tube, the mercury will fall away from the upper end of the tube, in spite of the fact that in so doing it will leave a vacuum above it; and its upper surface will in fact stand about $\frac{1}{13}$ of 32 ft (that is, between 29 and 30 in.) above the mercury in the dish.

Torricelli concluded from this experiment that the rise of liquids in exhausted tubes is due to an outside pressure exerted by the atmosphere on the surface of the liquid, and not to any mysterious sucking power created by the vacuum, as is popularly believed even today.

Further decisive tests. An unanswerable argument in favor of this conclusion will be furnished if the mercury in the tube falls as soon as the air is removed from above the surface of the mercury in the dish.

To test this point let the dish and the tube be placed on the table of an air pump, as in Fig. 31, the tube passing through a tightly fitting rubber stopper A in the bell jar. As soon as the pump is started, the mercury in the tube will, in fact, be seen to fall. As the pumping is continued, it will fall nearer and nearer to the level in the dish, although it will not usually reach it, for the reason that an ordinary air pump is not capable of producing so low a pressure as that which exists in the top of the tube. As the air is allowed to return to the bell jar, the mercury will rise in the tube to its former level.

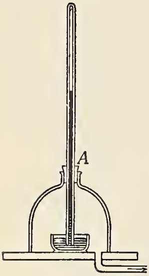


FIG. 31. Barometer falls when air pressure on the mercury surface is reduced

Amount of the atmospheric pressure. Torricelli's experiment shows exactly how great the atmospheric pressure is, since this pressure is able to balance a column of mercury of definite length. As the pressures along the same level *ac* (Fig. 32) are equal, the downward pressure exerted by the atmosphere on the surface of the mercury at c is equal to the downward pressure of the column of mercury at a. But the downward pressure at this point within the tube is equal to hd, where d is the density of the mercury and h is the depth below the surface b. Since the average height of this column at sea level is found to be 76 centimeters (about 30 inches), and since the density of mercury is 13.6 grams per cubic centimeter, the downward pressure inside the tube at a is equal to 76 times 13.6 grams, or 1033.6 grams per square centimeter. Therefore the atmospheric pressure acting on the surface of the mercury at c is 1033.6 grams, or approximately 1 kilogram, per square centimeter. In English units

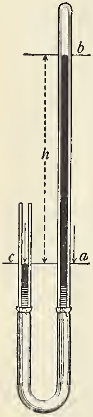


FIG. 32

$$\begin{aligned} p &= h \times d \\ &= \tfrac{30}{12} \times 62.4 \times 13.6 \\ &= 2121.6 \text{ lb/ft}^2 \\ &= 14.7 \text{ lb/in.}^2 \end{aligned}$$

The pressure of one atmosphere is, then, about 15 pounds per square inch, or about 1 ton per square foot. This pressure makes its way through tiny cracks and crevices even into tightly closed buildings, so that the pressure inside is the same as outside. A tornado is a storm area of extremely low pressure. When it suddenly surrounds a closed house, the air inside does not have time to seep through the cracks, so it pushes the windows outward, as is shown by the fact that the broken glass is found on the outside.

Pascal's experiment. Pascal thought of another way of testing whether or not it is indeed the weight of the outside air which sustains the column of mercury in an exhausted tube. He reasoned that since the pressure in a liquid diminishes on ascending toward the surface, atmospheric pressure ought also to diminish as one passes from sea level to a mountaintop. As there was no mountain near Paris, he carried Torricelli's apparatus to the top of a high tower and found, indeed, a slight fall in the height of the column of mercury. He then wrote to his brother-in-law, Perrier, who lived near Puy-de-Dôme, a mountain in southern France, and requested him to perform the experiment on a larger scale. Perrier wrote back that he was "ravished with admiration and astonishment" when he observed that on ascending 1000 meters (or $\frac{5}{8}$ of a mile) the mercury sank about 8 centimeters (or about 3 inches) in the tube. This was in 1648, five years after Torricelli's discovery.

At the present time airplane pilots, balloonists, and geological parties measure altitude by observing the change in barometric pressure as they ascend or descend. For comparatively small elevations the barometer falls 0.1 inch for every 90 feet of ascent.

The barometer. The modern barometer (Fig. 33) is essentially nothing more nor less than Torricelli's tube. Taking a barometer reading consists simply in measuring accurately the height of the mercury column. As the pressure changes from day to day, the level of the mercury in the bottom cup changes likewise, and must be brought back to

the zero of the scale (marked by the point of a small ivory "tooth") by an adjusting screw on the bottom before each reading is taken. A vernier scale allows the height of the mercury to be read with greater accuracy. This height varies from 73 to 76.5 centimeters in localities which are not far above sea level, the reason being that disturbances in the atmosphere affect the pressure at the earth's surface in the same way in which eddies and high waves in a tank of water affect the liquid pressure at the bottom of the tank.

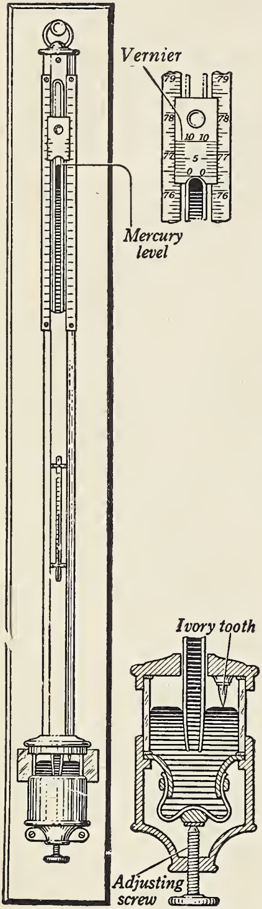
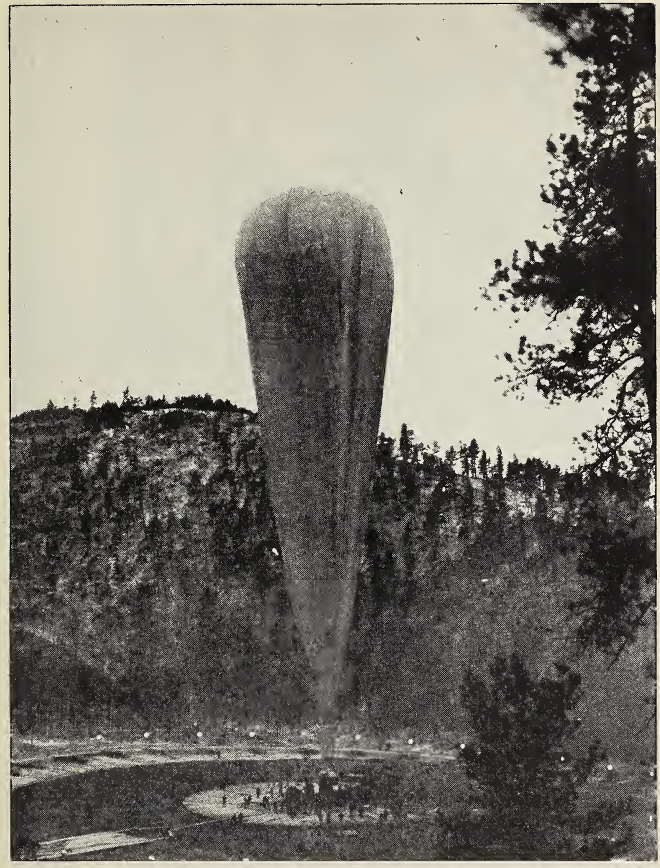


FIG. 33. A mercury barometer

The barometer does not directly foretell the weather, but it has been found that a low or rapidly falling pressure is usually accompanied (or soon followed) by stormy conditions. Hence the barometer, although it is not an infallible weather prophet, is nevertheless of considerable assistance in forecasting weather conditions some hours ahead. Further, by comparing at a central station the telegraphic reports of barometer readings made every few hours at stations all over the country, it is possible to determine in what direction the atmospheric eddies responsible for barometer changes and stormy conditions are traveling and hence to forecast the weather even a day or two in advance.

[**The first barometers.** Torricelli actually constructed a barometer



The Largest Balloon ever Built

Poised for its take-off, November 11, 1935, in the National-Geographic-Society-United-States-Army-Air-Corps Stratosphere Flight from Stratobowl, near Rapid City, South Dakota. The volume of the bag was 3,700,000 cubic feet; weight of the balloon, gondola, and contents, about 250,000 pounds. There were 2 acres of balloon fabric

The Original Magdeburg Hemispheres

This picture is on the cover of the book which describes the experiments of Otto von Guericke. In the presence of Emperor Ferdinand III sixteen horses are trying to separate the Magdeburg hemispheres, after the air between them has been exhausted. These hemispheres are still preserved in the museum at Berlin. Their interior diameter is 22 inches. Guericke invented the air pump (1650) and performed with it many spectacular experiments

not essentially different from that shown in Fig. 33 and used it for observing changes in the atmospheric pressure; but perhaps the most interesting of the early barometers was that which was set up about 1650 by Otto von Guericke (1602–1686), mayor of Magdeburg, Germany. He used for his barometer a column of water the top of which passed through the roof of his house. A wooden image, floating on the upper surface of the water, appeared above the housetop in fair weather but retired from sight in foul, a circumstance which led his neighbors to charge him with being in league with Satan.

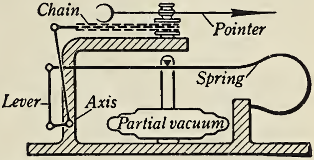


FIG. 34. Sectional view of an aneroid barometer

The aneroid barometer. Since the mercury barometer is somewhat long and inconvenient to carry, geological and surveying parties commonly use an instrument called the

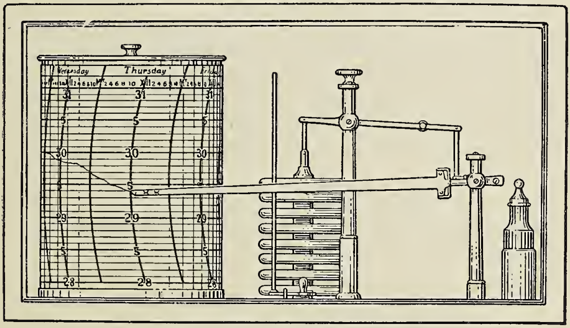


FIG. 35. The aneroid barograph

aneroid barometer. It consists essentially of one or more air-tight cylindrical boxes, the top of each one being a metallic diaphragm which bends slightly under the influence of change in the atmospheric pressure. This motion is multiplied by a delicate system of levers and is communicated to

a hand which moves over a dial whose readings are made to correspond to the readings of a mercury barometer. These instruments are made so sensitive as to indicate a change in pressure when they are moved no farther than from a table to the floor. In the self-recording aneroid barometer, or barograph, used by the United States Weather Bureau (Fig. 35), several of the airtight boxes are superposed for greater sensitiveness, and the pressures are recorded in ink upon paper wound about a drum. Clockwork inside the drum makes it revolve once a week. The altimeter, as used in airplanes to indicate their altitude, is essentially an aneroid barometer marked off directly in feet of altitude instead of in inches or centimeters of mercury.

Summary. **Air has weight, 1 cubic centimeter at 0° C. weighing .001293 gram and 1 cubic foot weighing $\frac{4}{3}$ ounce. Because of its weight the atmosphere exerts a pressure at sea level of 76 centimeters (30 inches) of mercury, the equivalent of 1033.6 grams (about 1 kilogram) per square centimeter, or 14.7 pounds per square inch.**

Atmospheric pressure diminishes with ascent, a fall of 1 millimeter in the barometer corresponding to an ascent of about 12 meters for relatively small distances above the sea level.

Weather forecasts are based only in part upon barometric readings. A rapidly falling barometer is usually accompanied or followed by a storm.

QUESTIONS AND PROBLEMS

[In working problems involving the use of pi, it will be sufficiently accurate to use $\frac{22}{7}$ unless otherwise instructed.]

A

1. From the barograph reading, Fig. 35, could you make a prediction of the probable coming weather?

2. Would the pressure of the atmosphere hold mercury as high in a tube as large as your wrist as in one having the diameter of your finger? Explain.

3. Measure the dimensions of your classroom in feet and calculate the number of pounds of air in the room.

4. The body of the average man has 15 ft^2 of surface. (*a*) What is the total force of the atmosphere upon him? (*b*) Why is he not conscious of this crushing force?

5. What would happen to a barometer reading (*a*) if a pinhole were made in the top of the barometer tube? (*b*) if the tube were somewhat inclined?

6. If a tumbler is filled or nearly filled with water, and a piece of writing paper is placed over the top, it may be inverted, as in Fig. 36, without spilling the water. Explain. What is the function of the paper?

FIG. 36

7. Make a labeled drawing of a simple Torricellian barometer, naming all the parts in the diagram.

8. If the variation of the height of a mercury barometer was 2 in., how far did the image rise and fall in Guericke's water barometer?

9. If the experiment shown in Fig. 29 was not done in class, perform it as a home project, and bring the crushed can to school as an exhibit.

B

1. Express the numerical value of ordinary air pressure in six different ways.

2. Give three reasons why mercury is better than water for use in barometers.

3. Find the atmospheric pressure in grams per square centimeter when the barometer reads 76 cm.

4. Find the atmospheric pressure (*a*) in pounds per square inch when the barometer reads 29.50 in.; (*b*) in grams per square centimeter when it reads 74.50 cm.

5. A balloonist once rose to such a height that his barometer read 18 cm. What was the pressure of the atmosphere?

6. If a barometer fell from 30.5 in. to 28.75 in. during the passing of a severe storm, how much did the pressure change in pounds per square inch?

7. Magdeburg hemispheres (see opposite page 51) are so called because they were invented by Otto von Guericke, who was mayor of Magdeburg. When the lips of the hemispheres are placed in contact and the air exhausted from between them, it is found very difficult to pull them apart. Why?

8. Guericke's original hemispheres were 22 in. in interior diameter. If the air was all removed from the interior of the hemispheres, what force in pounds was in fact required to pull them apart? (Find the atmospheric force on a circle with a radius of 11 in.)

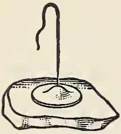


FIG. 37

9. Explain the process of making lemonade rise in a straw.

10. If a circular piece of wet leather having a string attached to the middle is pressed down on a flat, smooth stone, as in Fig. 37, the latter may often be lifted by pulling on the string. Why do the stone and the leather not separate while you are lifting them?

11. Why does not the ink run out of a pneumatic inkstand like that shown in Fig. 38?

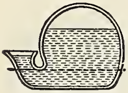


FIG. 38

12. If a small quantity of air should get into the space at the top of the mercury column of a barometer, how would it affect the readings? Why?

13. If the pressure at a depth of 30 in. ($2\frac{1}{2}$ ft) in mercury is 1 atmosphere, at what depth in feet would you expect the pressure of water to be (*a*) 1 atmosphere? (*b*) 2 atmospheres? (*c*) 3 atmospheres? (Specific gravity of mercury = 13.6.)

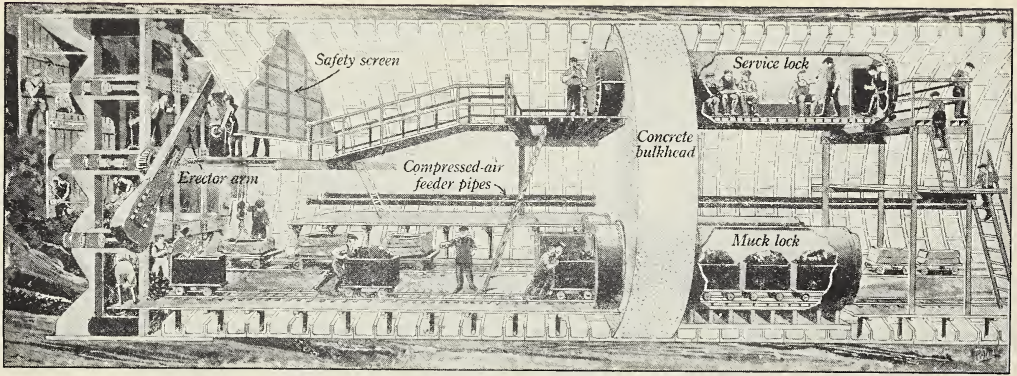
14. Calculate the number of tons of atmospheric force on the roof of an apartment house 50 ft × 100 ft. Why does the roof not cave in?

Compressibility and Expansibility of Air

Incompressibility of liquids. Thus far we have found very striking resemblances between the conditions which exist at the bottom of a body of liquid and those which exist at the bottom of the great ocean of air in which we live. We now come to a most important difference. It is well known that if 2 liters of water be poured into a tall cylindrical vessel, the water will stand exactly twice as high as if the vessel contained but 1 liter; or if 10 liters be poured in, the water will stand ten times as high as if there were but 1 liter. This means that the lowest liter in the vessel is not compressed by the weight of the water above it.

Start of a Record-Making Flight

Captains A. W. Stevens and O. A. Anderson entering the gondola before beginning their flight, record-making for a manned balloon, on November 11, 1935. (Courtesy of the National Geographic Society)



Underwater Tunnel Construction

In constructing underwater tunnels, the workers are compelled to operate under an air pressure great enough to withstand the pressure which would force earth and muck into the space where they work. As material is removed (see left end of picture), powerful jacks press forward a cylindrical shield, inside of which the tunnel lining of cast-iron segments is built up. A concrete bulkhead separates the compressed-air working chamber at the left from the space at the right, where atmospheric pressure exists. To enter the high-pressure compartment, the men pass first into the service lock, and remain there for several minutes while the air pressure upon them is gradually increased. This is called "compressing" the men. In this way the blood becomes charged with dissolved air which enters by way of the lungs. To leave the high-pressure compartment, the men again enter the service lock while the pressure is gradually lowered to that of the atmosphere outside to permit the excess dissolved gases to leave the blood by way of the lungs. If this "decompressing" is done too rapidly, the dissolved gases escape as bubbles within the blood vessels, which causes intense pain, and sometimes death results. Small cars loaded with diggings of rock, earth, and muck are taken out through the locks as shown at the bottom. (Courtesy of the *Popular Science Monthly*)

Careful experiments show that compressing forces enormously greater than these may be used without producing a marked effect; for example, when a cubic centimeter of water is subjected to the tremendous pressure of 3000 kilograms per square centimeter (3.3 tons), its volume is reduced to but 0.90 cubic centimeter. This means that at a depth of six miles in the ocean a given volume of water is diminished only about 4 per cent. Hence we say that water, and liquids generally, are practically incompressible. Had it not been for this fact we should not have been justified in taking the pressure at any depth below the surface of the sea as the simple product of the depth by the density at the surface, because the numerical value of the density would change with the depth.

Compressibility of gases. When we exert a pressure on air or on any other gas, we find that it acts very differently from water or other liquids. Every time we inflate an automobile tire, we prove that air may be compressed to one half, one fifth, or one tenth its normal volume. Further, the *expansibility* of air (that is, its tendency to spring back to a larger volume as soon as the pressure is decreased) is proved every time a tennis ball or a football bounces or the air rushes out from a punctured tire.

But this readiness to expand as soon as the pressure is diminished does not belong merely to air which has been crowded into a pneumatic cushion by some sort of pressure pump; the ordinary air of the room will expand in the same way if the pressure on it is made less.

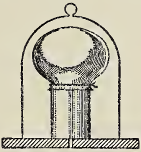


Fig. 39

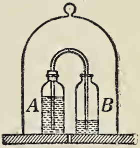


Fig. 40

Illustrations of the expansibility of air

Thus if a liter beaker with a sheet of rubber dam tied tightly over the top is placed under the receiver of an air pump, as soon as the pump is set into operation the inside air will expand with sufficient force to burst the rubber or greatly distend it, as shown in Fig. 39.

Again, arrange two bottles as in Fig. 40, one being stoppered airtight, and the other left uncorked. As soon as the two are placed under the receiver of an air pump and the air is exhausted, the water in A will pass over into B. When the air is readmitted to the receiver, the water will flow back. Explain.

Why hollow bodies are not crushed by atmospheric pressure. The preceding experiments show why the walls of hollow bodies are not crushed in by the enormous forces which the weight of the atmosphere exerts against them. Thus at normal atmospheric pressure a soap bubble $6\frac{1}{2}$ inches in diameter is under a total crushing force of one ton; but the air inside such bodies presses their walls out with as much force as the outside air presses them in. In the experiment on page 46 the inside air was removed by the escaping steam. When this steam was condensed by the cold water, the inside pressure became very small, and the outside pressure then crushed the can. In the experiment shown in Fig. 39 it was the outside pressure which was reduced by the air pump. The air inside then expanded until its pressure finally burst the rubber.

Boyle's law. The first man to investigate the exact relation between the change in the pressure exerted by a confined body of gas and its change in volume was Robert Boyle, born in Ireland in 1627. A modified form of his experiment should be repeated carefully in the laboratory, but the following will illustrate the method by which he discovered the important law which is now known by his name:

Pour mercury into a bent glass tube (a manometer) until it stands at the same level in both arms (Fig. 41 (*a*)). There is now in AC a certain volume of air under a pressure of one atmosphere. (Why?) Call this pressure P_1. Measure the length AC and call it V_1. Now pour mercury into the tube (Fig. 41 (*b*)) until the level in the long arm is as many centimeters above the level in the short arm as there are centimeters in the height of the barometer. The confined air V_2 is now under the pressure of *two* atmospheres. (Why?) Measure the new volume A_1C. It will be found to be just half its former value.

Hence we learn that doubling the pressure exerted upon a body of gas halves its volume. If we had tripled the pressure, we should have found the volume reduced to one third its initial value, and so on. That is, *the pressure which a given quantity of gas at constant temperature exerts against the walls of the containing vessel is inversely proportional to the volume occupied.* This may be algebraically stated as follows:

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}, \text{ or } P_1V_1 = P_2V_2. \qquad (1)$$

This is Boyle's law. (Later investigations show that for extremely high pressures certain corrections must be made.) Since, as the pressure increases, the volume decreases proportionally, the product of every pressure by its corresponding volume is always a constant quantity. Stated algebraically, Boyle's law takes the simple form

$$PV = C. \qquad (2)$$

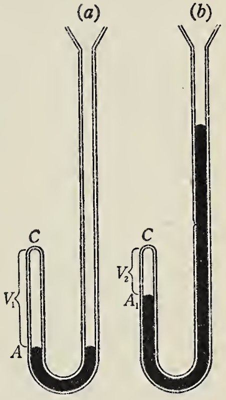


FIG. 41. Method of demonstrating Boyle's law

The effect of pressure may also be stated in another form. Doubling, tripling, or quadrupling the pressure must double, triple, or quadruple the *density*, since the volume is made only one half, one third, or one fourth as much, while the mass remains unchanged. Hence *the pressure which a gas exerts at constant temperature is directly proportional to its density,**

$$\frac{P_1}{P_2} = \frac{D_1}{D_2}, \text{ or } P_1D_2 = P_2D_1, \qquad (3)$$

where D_1 and D_2 are the gas densities corresponding to the gas pressures P_1 and P_2, respectively.

* A laboratory experiment on Boyle's law should follow this discussion. See, for example, Experiment 8 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

To transport gases economically and conveniently pressures as high as 1800 pounds per square inch are used to compress them in strong steel cylinders. Oxygen in such condition is sold widely for the treatment of the sick, for cutting and welding metals, and for aviators at high altitudes. Carbon dioxide is also furnished to soda fountains in cylinders.

Measurement of gas pressure. For measuring gas and steam pressures various types of gauges are used, the Bourdon being one of the best. Fig. 42 (*b*) shows a simple form of this gauge for use with automobile tires. A flattened tube (Fig. 42 (*a*)) is bent into the form of an arc, so that when air under pressure enters it the tube tends to straighten. This causes the rack R to turn the pinion P, to which the pointer is attached. These gauges, as well as steam gauges, record whatever pressure exists *in excess of the atmospheric pressure.* In general, *absolute (or total) pressure equals gauge pressure + 14.7 pounds per square inch at sea level.**

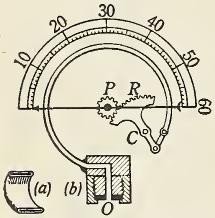


FIG. 42. Interior of Bourdon type of tire-pressure gauge

The extent and character of the earth's atmosphere. While man has made his way all over the earth's surface, his vertical explorations have been limited by pressure difficulties to a few miles up and a few thousand feet down from the earth's level. Tremendous pressures block his downward explorations undersea, and diminishing pressures, with extreme cold, hinder his upward conquests in the air.

From the facts of compressibility and expansibility of air we know that the air, unlike the sea, must become less and less dense as we ascend from the bottom toward the top. Thus at the summit of Mont Blanc, an altitude of about three miles, where the barometer height is but 38 centimeters,

* It is recommended that laboratory work on the use of manometers accompany this discussion. See, for example, Experiment 9 of *Exercises in Laboratory Physics.* by Millikan, Gale, and Davis.

or one half its value at sea level, the density also must, by Boyle's law, be just one half as much as at sea level. How rapidly the properties of the atmosphere change with altitude is indicated by the data given in Fig. 43.

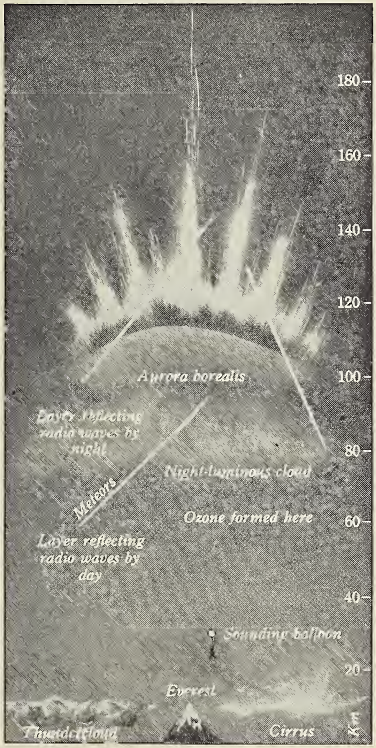


FIG. 43. Extent and character of atmosphere. (After Dobson)

At the higher altitudes the lungs cannot receive enough oxygen to support life. By applying the methods of modern science, however, man has pushed his knowledge of the upper air to higher points each year. In these attempts oxygen is inhaled artificially, and the men are incased in electrically heated suits. Even airplane engines must be given more oxygen by the use of the supercharger in order that they may operate in the thin air. On April 11, 1934, Commander Renato Donati of the Italian air force succeeded in setting a new altitude record for airplanes when he reached a height of 47,352 feet, or almost 9 miles above sea level, where the barometer stood at only about 10 centimeters. In this flight he used a Caproni plane of 530 horsepower.

On November 11, 1935, at Rapid City, South Dakota, Captain Albert W. Stevens and Captain Orvil A. Anderson, United States army officers, ascended to a height of 72,395 feet, or more than 13.7 miles. The trip was made in a hollow metal sphere tightly sealed and attached to a huge helium-filled balloon. (See opposite pages 50 and 54.)

The upper portion of the earth's atmosphere, the region above 11 kilometers, is called the *stratosphere*. Here the temperature changes but little with altitude, and water clouds never form.

By sending up self-registering thermometers and barometers in balloons which burst at great altitudes (the instruments being protected by parachutes from the dangers of rapid fall), the atmosphere has been explored to a height of 35,900 meters (22.3 miles), this being the height attained on September 8, 1930, by a sounding balloon which was sent up at Hamburg, Germany. Pilot balloons, carrying no instruments, have reached heights of more than 24 miles.

At a height of 35 miles the density of the atmosphere is estimated to be but $\frac{1}{30,000}$ as great as at sea level. By calculating how far below the horizon the sun must be when the last traces of color disappear from the sky, we find that at a height as great as 45 miles there must be air enough to reflect some light. How far beyond this an extremely rarefied atmosphere may extend, no one knows. It has been estimated at all the way from 100 to 500 miles. These estimates are based on observations of the height at which meteors first become visible, on the height of the aurora borealis, and on the darkening of the surface of the moon just before it is eclipsed by the shadow of the solid earth.

Summary. **Liquids, being practically incompressible, exert pressure proportional to depth below the free surface.**

Gases, being highly compressible, do not follow the depth-pressure law.

Boyle's law. **The pressure exerted by a given mass of gas at constant temperature is inversely proportional to its volume or directly proportional to its density.**

QUESTIONS AND PROBLEMS

[Assume in these problems that the temperature is kept constant.]

A

1. Blow as hard as possible into the tube of the bottle shown in Fig. 44. Then withdraw the mouth and explain all the effects observed.

2. What sort of change in volume do the bubbles of air which escape from a diver's suit experience as they ascend to the surface?

FIG. 44

3. With the aid of the experiment in which the rubber dam was burst under the exhausted receiver of an air pump, explain why high mountain climbing often causes pain and bleeding in the ears and nose.

4. Pressure tests for boilers or steel tanks of any kind are always made by filling them with water rather than with air. Why?

5. The deepest sounding in the ocean is about 6 mi. Find the pressure in tons per square inch at this depth. (Specific gravity of ocean water = 1.026.)

6. The pressure gauge on an air-storage tank reads 85 lb/in.^{2} What is the absolute pressure?

7. There is a pressure of 80 cm of mercury on 1000 cm^3 of gas. What pressure must be applied to reduce the volume to 600 cm^3?

B

1. If 100 ft^3 of hydrogen gas at normal pressure is forced into a steel tank having a capacity of 5 ft^3, (*a*) what is the absolute gas pressure in pounds per square inch? (*b*) what is the gauge pressure?

2. A gas cylinder 5 ft long and 1 ft^2 in cross section contains gas at a gauge pressure of 210 lb/in.^{2} How many cubic feet would this gas occupy at normal atmospheric pressure?

3. Compare equations (1) and (3) on page 57; how does the arrangement of the subscripts (figures written beneath) distinguish a direct proportion from an inverse proportion?

4. An automobile tire having a capacity of 1500 in.^{3} is inflated to a gauge pressure of 35 lb/in.^{2} (*a*) What is the density of the air within the tire? (*b*) To what volume would the released air expand?

5. Find the density of air on a mountain where the barometer reads 50 cm, if the density at sea level is .00118.

6. A glass tube 25 in. long and closed at the upper end is attached to the sounding lead of a ship. On drawing the lead from the bottom of the ocean, the sea water is found to have wet 24 in. of the inner surface of the tube. (*a*) How many atmospheres of pressure acted upon the air inclosed in the tube? (*b*) How many were due to the water? (*c*) How many fathoms (a fathom = 6 ft) deep was the ocean (the density of ocean water being 64 lb/ft^3)?

7. Under ordinary conditions a gram of air occupies about 800 cm^3. Find what volume a gram will occupy at the top of Mont Blanc (altitude 15,781 ft), where the barometer indicates that the pressure is only about one half what it is at sea level.

8. The mean density of the air at sea level is about .0013 g/cm^3. (*a*) What is its density at the top of Mont Blanc? (*b*) What fractional part of the earth's atmosphere has one left beneath him when he ascends to the top of this mountain?

9. If a diver's tank has a volume of 2 ft^3 and contains air under a pressure of 40 atmospheres, to what volume will the air expand when it is released at a depth of 34 ft under water?

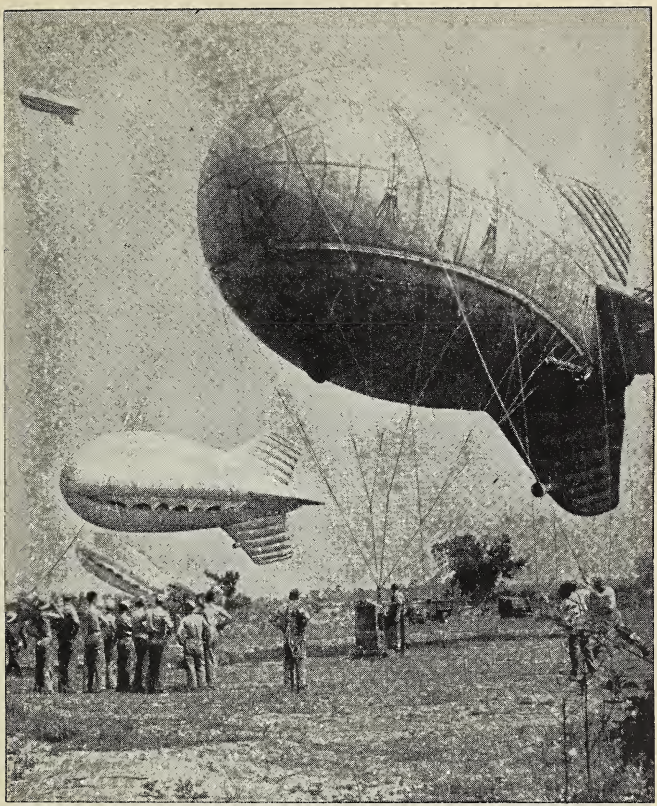
10. A gas tank having a capacity of 2 ft^3 contained acetylene at a gauge pressure of 1845 $lb/in.^2$. When the gauge pressure fell to 915 $lb/in.^2$, how many cubic feet of the gas were used?

11. At the earth's surface 1 cm^3 of air weighs .00129 g. If this were the density all the way up, (*a*) to what height in kilometers would the atmosphere extend? (*b*) How many miles?

12. Physicians measure the blood pressure of their patients in making a physical examination. Explain how it is done and in what units it is measured.

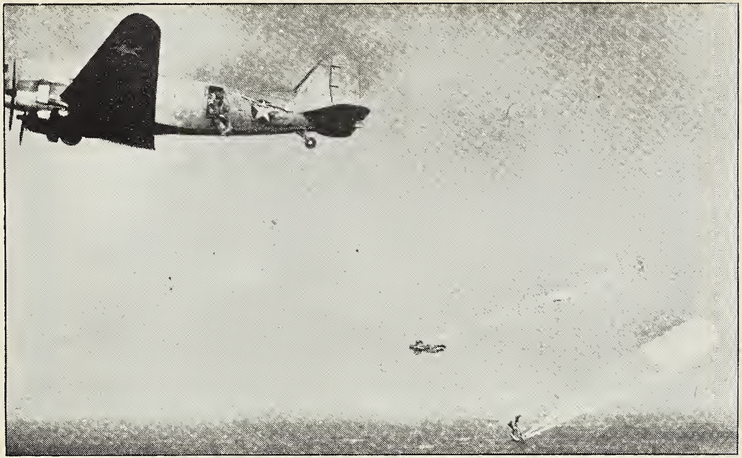
Pneumatic Appliances

Introductory. In the preceding pages we have learned the physical facts about gases. The next few pages describe some of the appliances which man has devised for using these facts to make his life easier and more complete. Students do not always see the necessity for studying the fundamental facts and laws of pure science, but they are necessary and important not only for an understanding of their practical



Barrage Balloons

Balloons have been used in warfare since 1799, usually for observation purposes. In the present World War they have found a greater usefulness for barrage purposes. Balloons are sent up to which are attached networks of cables for the entanglement of bombers. Peacetime use of the balloon includes meteorological observation. Either self-recording instruments may be carried aloft or free balloons may be liberated and their drift observed as an indication of air currents. Balloons are generally inflated with hydrogen. The material of the above balloon is varnished silk. (Courtesy of U. S. Marine Corps)



Parachutes

Parachutes, acting on the principle of an opened umbrella, have long been used to break the fall from balloons. In 1797 a parachutist dropped safely from an altitude of 3000 feet. Descents of more than five miles have been recorded. A parachute averages 24 feet in diameter and weighs about 18 pounds. It is made of silk or nylon. It is attached to the aviator by shoulder and leg straps. Upon jumping, and after having cleared a safe distance, the aviator may release the parachute by pulling a rip cord. The descent is at the rate of about 15 feet per second and it should not be attempted from less than five hundred feet. Not only has the parachute been used in emergency landings, but it has also been used to deliver cargo, food, and medicine to isolated bodies of troops. (Courtesy of U. S. Navy)

applications already in existence but also for the invention of new and better ones.

The siphon. Fill a rubber or glass tube with water and place it in the position shown in Fig. 45. Water will be found to flow through the tube from vessel *A* into vessel *B*. If *B* is then raised until the water in it is at a higher level than that in *A*, the direction of flow will be reversed. This instrument, which is called the *siphon*, is very useful for removing liquids from vessels which cannot be overturned, or for drawing off the upper layers of a liquid without disturbing the lower layers.

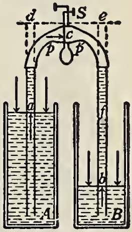


FIG. 45. The siphon

The explanation of the action of the siphon is readily seen from Fig. 45. Since the tube *acb* is full of water, water must evidently flow through it if the force which pushes it one way is greater than that which pushes it the other way. Now the upward pressure at *a* is equal to the atmospheric pressure minus the downward pressure of the water column *ad*, and the upward pressure at *b* is the atmospheric pressure minus the downward pressure of the water column *be*. Hence the pressure at *a* exceeds the pressure at *b* by the pressure of the water column *fb*. The siphon will evidently cease to operate when the water is at the same level in the two vessels, since then $fb = 0$, and the forces acting at the two ends of the tube are therefore equal and opposite. It will also cease to act when the bend *c* is more than 34 feet above the surface of the water in *A*, atmospheric pressure being unable to raise water to a height greater than this in either tube.

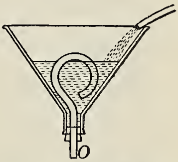


FIG. 46. The intermittent siphon

Would a siphon flow in a vacuum?

The intermittent siphon. Fig. 46 represents an intermittent siphon. If the vessel is at first empty, to what level must it be filled before the water will flow out at *O*? To what level will the water then fall before the flow ceases? This principle finds use in public toilets which are to be flushed automatically at regular intervals.

The air pump. The air pump was invented in 1650 by Otto von Guericke. He deserves great credit, since he was apparently ignorant of the discoveries which Galileo, Torricelli, and Pascal had made a few years earlier regarding the earth's atmosphere. A simple form of such a pump is shown in Fig. 47. When the piston is raised, the air from the receiver *R* expands into the cylinder *B* through the valve *A*. When the piston descends, it compresses this air and thus closes the valve *A*, opening, in turn, the exhaust valve *C*. Thus with each double stroke a certain fraction of the air contained in the receiver is transferred from *R* through the cylinder to the outside. In many pumps the valve *C* is located in the piston itself.

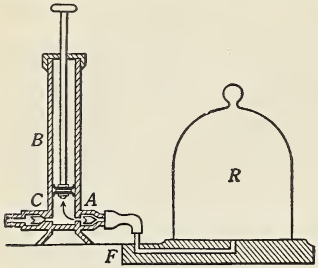


FIG. 47. A simple air pump

Owing to certain defects, such a pump can produce only a moderate vacuum; that is, it can reduce the pressure only so that a barometer would read 2 or 3 centimeters instead of about 76 centimeters. For scientific and industrial purposes, where very low pressures are required, complicated pumps have been devised to give a vacuum of less than 0.000001 millimeter.

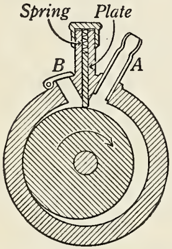


FIG. 48. Rotary pump

Rotary pumps, because of their simplicity and greater effectiveness, are widely used. They operate by means of an eccentric piston rotating within a close-fitting cylinder. The molecules, coming in at *A*, are caught in the very slight space between the cylinder and the piston and rolled round the circumference to the opening *B*, where they exhaust to the air. (See Fig. 48.)

Household vacuum cleaners use a small motor-driven rotary vacuum pump which is essentially a reversed electric fan. The dirt is drawn through a nozzle resting on the surface to be cleaned and is passed into a fabric bag which retains the particles of dirt and allows the air to escape through its pores. Some types contain a revolving brush to aid the cleaning process.

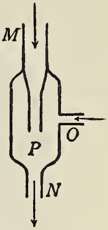


FIG. 49. Aspirator

The aspirator. The aspirator is a convenient, inexpensive device to produce a moderate degree of vacuum. It is much used in the chemistry laboratory to hasten the filtration of liquids, and by the dentist to keep a patient's mouth dry while a tooth is being filled.

FIG. 50. Atomizer

The opening O (Fig. 49) is attached to the vessel to be evacuated (pumped out), and M to a water faucet. As the water runs rapidly through P, it carries with it some of the air in P, thus reducing the pressure. The air in the vessel connected with O expands and flows into P, where the process is continually repeated.

The atomizer. If a stream of air be blown across the opening of the tube T (Fig. 50), a partial vacuum will be created in it. The pressure of the air in the bottle causes the liquid to rise in the tube, at whose mouth it is broken up into a fine spray by the force of the air current. Such a device is widely used in painting automobiles and furniture (here called a paint gun), in spraying orchards, in applying perfume, and in spraying the nose and the throat.

FIG. 51. The ball and jet

The atomizer principle is shown naturally in the increased draft found in chimneys on a windy day. The wind blowing across the mouth of the chimney creates a partial vacuum therein, so that a stronger current of air rushes upward.

The ball and jet (Fig. 51) is another application of the same principle. An area of reduced pressure along the edge of the jet is produced precisely as in the atomizer, and the ball is thus continually forced back to the jet by the outside atmospheric pressure.

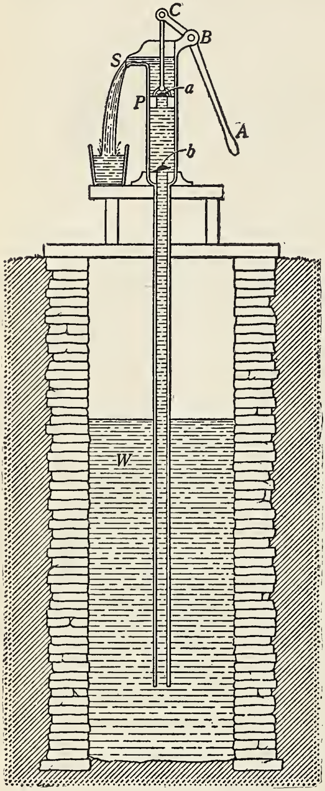


FIG. 52. The lift pump

The compression pump. A compression pump is used for compressing a gas into a container. If the pump shown in Fig. 47 is detached from the receiver plate, and the vessel to receive the gas is attached at *C*, we have a compression pump.

Compressed air finds so many applications in such machines as air drills (used in mining), air brakes, air motors, etc. that the compression pump must be regarded as of much greater importance industrially than the exhaust pump.

The lift pump. The common water pump, shown in Fig. 52, has been in use at least since the time of Aristotle (fourth century B.C.). It will be seen from the figure that it is nothing more nor less than a simplified form of air pump. In fact, in the earlier strokes we are simply exhausting air from the pipe below the valve *b*. Water could never be obtained at *S*, even with a perfect pump, if the valve *a* did not work within

34 feet of the surface of the water in *W*. Why? On account of mechanical imperfections this limit is usually about 28 feet instead of 34. Let the student analyze, stroke by stroke, the operation of pumping water from a well with the pump of Fig. 52. Why will pouring in a little water at the top — that is, priming — often assist greatly in starting such a pump? Pumps used in very deep wells are constructed with long plunger rods to bring the piston *P* to within the necessary distance of the water for successful operation.

The force pump. Fig. 53 illustrates the construction of the force pump, a device at least two thousand years old. The force pump is commonly used when it is desired to deliver water at a point higher than the position at which it is convenient to place the pump itself. Let the student analyze the action of the pump from a study of the diagram.

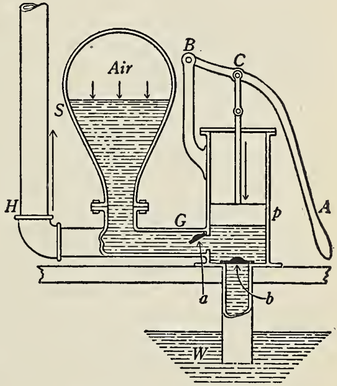


FIG. 53. The force pump

To make the flow of water in the pipe *H* continuous during the upstroke, an air chamber is inserted between the valve *a* and the discharge point. As the water is forced violently into this chamber by means of the downward motion of the piston, it compresses the confined air. It is the reaction of this compressed air that is directly responsible for the flow in the discharge tube; and as this reaction is continuous, the flow is continuous.

[**The Cartesian diver.** Descartes (1596–1650), the great French philosopher, invented an odd device which illustrates at the same time the principle of the transmission of pressure by liquids, the principle of Archimedes, and the compressibility of gases. A hollow glass image in human shape (see

Fig. 54 (*a*)) has an opening in the lower end. It is filled in part with water and in part with air, so that it will just float. By pressing on the rubber diaphragm at the top of the vessel it may be made to sink or rise at will. Explain. If the diver is not available, a small bottle or test tube (Fig. 54 (*b*)) may be used instead; it works equally well and brings out the principle even better. The modern submarine (see opposite page 41) is essentially nothing but a huge Cartesian diver propelled, above water, by Diesel engines, and, when submerged, by electric motors driven by storage batteries. The volume of air in its chambers is changed by forcing water in or out, and it dives by a combined use of the propeller and the horizontal rudders.

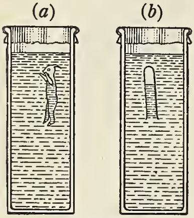


FIG. 54. The Cartesian diver

The balloon. A reference to the proof of Archimedes' principle (see page 38) will show that it must apply as well to gases as to liquids. Hence *any body immersed in air is buoyed up by a force which is equal to the weight of the displaced air.* The body will therefore rise if its own weight is less than the weight of the air which it displaces. When these weights become equal, the body floats.

A balloon is a large silk bag impregnated with rubber and usually filled either with hydrogen or with common illuminating gas. The former gas weighs about .09 kilogram per cubic meter, and common illuminating gas weighs about .75 kilogram per cubic meter. It will be remembered that ordinary air weighs about 1.20 kilogram per cubic meter. It will be seen, therefore, that the lifting force of hydrogen per cubic meter (namely, $1.20 - .09 = 1.11$) is more than twice the lifting force of illuminating gas ($1.20 - .75 = .45$). From the weights given above it is easy to calculate the lifting power of any balloon whose volume is known.

Ordinarily a balloon is not completely filled at the start; for if it were, since the outside pressure is continually dimin-

ishing as it ascends, the pressure of the inside gas would cause an enormous strain on the bag and would surely burst it before it reached any considerable altitude if gas were not allowed to escape through an opening or valve. This wastes the gas. But if the balloon is only partly inflated at the start, it can increase in volume as it ascends by simply inflating to a greater extent. Thus a balloon which ascends until the pressure is but 7 centimeters of mercury should be only about one-fourth inflated when it is at the surface.

As a balloon ascends, its occupants have no control over its direction; they must drift in the direction of the prevailing winds. The airship, or dirigible, is a huge cigar-shaped balloon with a rigid skeleton structure, propelled by gasoline engines. Pioneered by Germany, a number of these have been built with ever increasing size. The most spectacular airship performance was the trip around the world, in 1929, of the German dirigible *Graf Zeppelin*. In charge of Dr. Hugo Eckener, the trip was completed, including all stops, in 21 days and 8 hours.

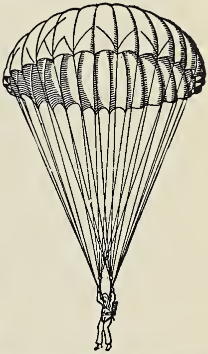


FIG. 55. The parachute

The parachute (see Fig. 55 and opposite page 63) is a huge umbrella-like affair with which the aeronaut may descend in safety to the earth. After opening, it descends very slowly on account of the enormous surface exposed to the air. A hole in the top allows air to escape slowly and thus keeps the parachute upright.

Helium balloons. One of the striking results of the World War was the development of the helium balloon. Helium is a noninflammable gas twice as dense as hydrogen and having a lifting power .92 as great. It is so rare an element that before the war not over 100 cubic feet had been collected by anyone. Its prewar price was $1700 per cubic foot. It is now being produced at a cost of about one cent a cubic foot

from the gas wells of Texas and Oklahoma. The production of a balloon gas that assures safety from fire opens up a new era for the dirigible balloon.

The diving suit. For most underwater work except that of heavy engineering the diving suit is used. This suit is made of rubber and has a metal helmet. The diver is usually connected with the surface by a tube through which air is forced down to him. It passes out into the water through a valve in his suit. But sometimes the diver is entirely independent of the surface, carrying air under a pressure of about 40 atmospheres in a tank on his back. This air is allowed to escape gradually through the suit and out into the water through a valve, as fast as the diver needs it. When he wishes to rise to the surface, he simply admits enough air to his suit to make him float.

[**The gas meter.** Gas from the city supply enters the meter through P (Fig. 56) and passes through the openings o and o_1 into the compartments B and B_1 of the meter. Here its pressure forces in the diaphragms d and d_1. The gas already contained in A and A_1 is therefore pushed out to the burners through the openings o' and o'_1 and the pipe P_1. As soon as the diaphragm d has moved as far as it can to the right, a lever which is worked by the movement of d causes the slide valve u to move to the left, thus closing o and shutting off connection between P and B, but at the same time opening o' and allowing the gas from P to enter compartment A through o'. A quarter of a cycle later u_1 moves to the right and connects A_1 with P and B_1 with P_1. If u and u_1 were set so as to work exactly together, there would be slight fluctuations in the gas pressure at P_1. The movement of the diaphragms is recorded by a clockwork device the dials of which indicate the number of cubic feet of gas consumed.

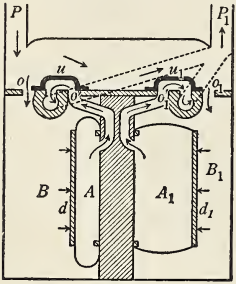
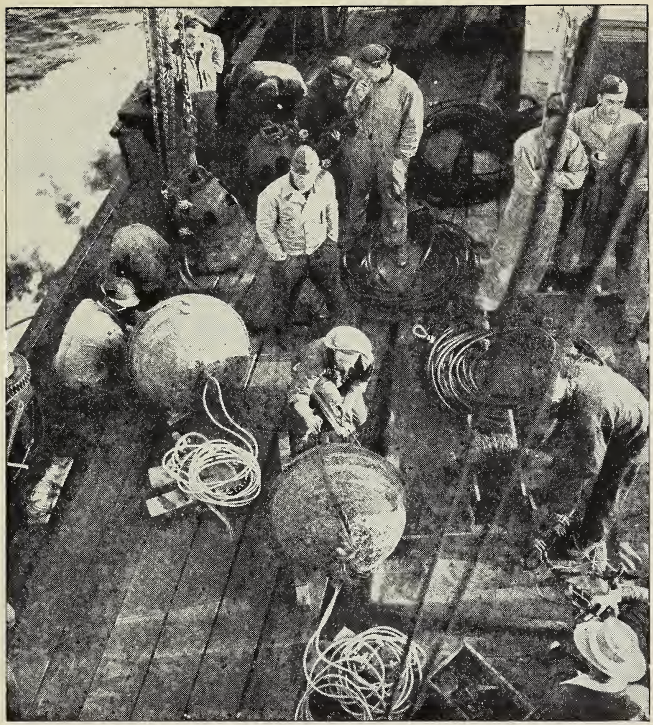


FIG. 56. The gas meter



Submarine Mines

Although submarine mines were used in earlier wars they became a most important factor in the First World War, in which a dramatic episode was the laying of the North Sea mine barrage. This illustration shows preparations for mine-laying. In laying mines the great danger is that of accidental detonation of a mine. Each submarine mine consists essentially of a watertight shell containing a high explosive. The controlled type of mine is exploded from a shore station by electricity. The contact type has four to five pins eight inches long, the contact of a ship with which sets off the detonation. A recently developed mine is the magnetic type, which is exploded through the influence of the magnetic field of the iron ship when it approaches near enough to the mine. Mines may be fixed by anchor and cable or may be free-floating. (Courtesy of Wide World)

Rescue Bell

On May 23, 1939, the submarine *Squalus* sank in a practice dive off Portsmouth, New Hampshire. In the first application of a rescue bell 33 of the 59 entrapped seamen were rescued. The submarine was 250 feet below the surface, at which depth there was a pressure of one hundred and twenty pounds per square inch. A diver descended and attached to the escape hatch the "down-haul" cable of the rescue bell. By means of a motor the bell descended until its rubber gasket closely adhered to the surface of the submarine. By means of compressed air, water was then pumped out of the lower chamber of the rescue bell, whereupon the bell's crew of two descended from the upper chamber of the bell, unfastened the escape hatch of the submarine, and liberated a number of the imprisoned men. The process was then reversed for ascent to the surface of the water. Four trips were necessary for the rescue of the thirty-three men. (Courtesy of Acme Photos)

[The heat energy which is obtained from the gas depends on its density. The density, according to Boyle's law, will vary with the pressure maintained in the gas mains. This pressure is checked periodically by city authorities, usually by a manometer similar to that of Fig. 57, and must be kept within certain limits.

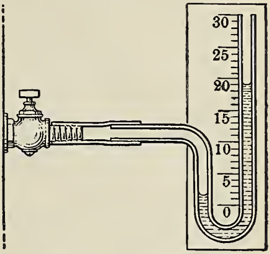


FIG. 57. Measuring gas pressure

[The gas is sold to the public at a certain cost per cubic foot (varying with the locality) or in terms of the newer unit, the therm. A therm is equal to 100,000 B.T.U. (See page 208.) The number of therms in a given volume of gas is found by multiplying the given number of cubic feet of gas by its number of B.T.U. per cubic foot as determined experimentally, and then dividing by 100,000. Monthly readings of the meter are made by the gas company. By subtracting the reading from that of the previous month, the amount of gas used by the customer during that month is obtained.

Summary. **The siphon flows because of unbalanced pressures within its unequal arms.**

An air pump is a device for removing air from a vessel by taking advantage of the natural tendency of gases to expand.

A lift pump must have its piston work within the limits of the height to which atmospheric pressure can raise a column of water.

A force pump can deliver water to any height.

Balloons rise or descend in accordance with Archimedes' law.

Divers are subject to the laws of liquid pressure and to Archimedes' law.

QUESTIONS AND PROBLEMS

A

1. Make a Cartesian diver at home out of a bottle, a small perfume vial, and a cork. Bring it to school as an exhibit and explain how it works. What principles of physics are illustrated?

2. Explain how a fountain pen is filled.

3. Make a siphon of the form shown in Fig. 58 by filling a flask one-third full of water, closing it with a cork through which pass two pieces of glass tubing, as in the figure, and then inverting so that the lower end of the straight tube is in a dish of water. If the bent arm is of considerable length, the fountain will play forcibly and continuously until the dish is emptied. Explain.

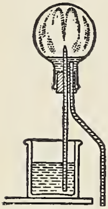


FIG. 58

4. A water tank 8 ft deep, standing some distance above the ground and closed everywhere except at the top, is to be emptied. The only means of emptying it is a flexible tube. (*a*) What is the most convenient way of using the tube, and how could it be set in operation? (*b*) How long must the tube be, in order to empty the tank completely?

5. Kerosene has a specific gravity of 0.8. Over what height can it be siphoned at normal pressure?

6. Describe the construction and explain the operation of the piston air pump, employed for exhausting a receiver.

B

1. If the cylinder of an air pump is of the same size as the receiver, (*a*) what fractional part of the air is removed by one complete stroke? (*b*) what fractional part is left after three strokes? (*c*) after ten strokes?

2. If the cylinder of an air pump is one third the size of the receiver, (*a*) what fractional part of the original air will be left after 5 strokes? (*b*) what will be the reading of a barometer within the receiver, the outside pressure being 76?

3. Theoretically can a vessel ever be completely exhausted by an air pump? (Suppose the pump to be mechanically perfect.)

4. Draw a diagram of a lift pump on the upstroke. (*a*) What causes the water to rise in the pipe? (*b*) What happens on the downstroke?

5. Draw a diagram of a force pump with an air dome, showing conditions on the downstroke. What happens on the upstroke?

6. At sea level what is the greatest height above the surface of the gasoline in a reservoir at which the upper piston of a perfect lift pump could operate? (The specific gravity of gasoline = .75.)

7. What determines how far a balloon will ascend? Explain by the principle of Archimedes.

8. If a balloonist wishes to descend, he causes the gas bag to become smaller by letting out some of the gas through a valve at the top. (*a*) Why does this allow the balloon to drop to a lower level? (*b*) How may he again ascend?

9. Explain, by reference to the weight of a balloon and the upward and downward forces of the atmosphere upon it, why it rises.

10. Hydrogen is lighter than air. Would pumping more of it into a balloon already expanded to its maximum capacity increase the lifting power of the balloon? Explain fully.

11. A liter of air weighs 1.29 g and a liter of helium 0.18 g at 0° C. If a small rubberized-silk balloon weighing 10 g is filled with 40 l of helium, what is its lifting power?

12. If air is forced into a caisson until the level of the water within it is 1033 cm beneath the surface of the river, to what fraction of its initial volume has the enclosed air been reduced? ($1033 \text{ g/cm}^2 = 1$ atmosphere.)

13. In Fig. 59 the upper figure shows a reading of 84,600 ft^3 of gas. The lower figure shows the reading of the meter a month later. (*a*) What was the amount of the bill for the month at 80 cents per 1000 ft^3? (*b*) Draw a diagram of the meter dials to represent 49,200 ft^3.

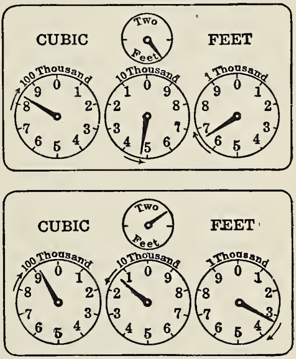


FIG. 59. The dials of a gas meter

14. Pneumatic dispatch tubes are used in many large stores for the transmission of small packages. An exhaust pump is attached to one end of the tube in which a tightly fitting carriage moves, and a compression pump to the other. If the air is half exhausted on one side of the carriage and has twice its normal density on the other, find the propelling force acting on the carriage when the area of its cross section is 50 cm^2.

15. A submarine weighs 1800 t when its submerging tanks are empty, and in that condition 10 per cent by volume of the submarine is above water. What weight of water must be let into the tanks in order just to submerge the boat?

16. Explain the process of breathing, both inhaling and exhaling.

CHAPTER IV

Molecular Motions

Kinetic Theory of Gases*

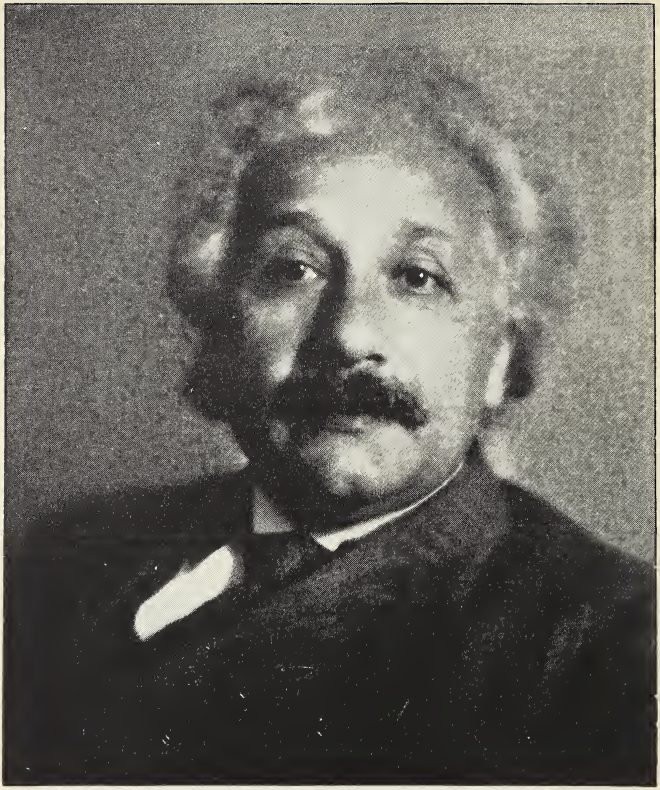
What matter is made of. A teaspoonful of sugar may be added to a full cup of coffee without causing it to overflow. In many other cases it is found that two substances after mixing occupy no more space than one of them occupied before. In order to account for such facts practically all physicists now assume that all matter, regardless of what it is, is made up of very tiny particles called *molecules*. Spaces exist between these molecules, so that when one gas enters a vessel which is already full of another gas, the molecules of the one scatter themselves about among the molecules of the other. Since molecules cannot be seen with the most powerful microscopes, it is evident that they must be exceedingly small. The number of them contained in a cubic centimeter of air at normal temperature and normal pressure is twenty-seven billion billion (27×10^{18}). It has been estimated that this is approximately the number of grains of sea sand required to fill a box 1 mile long, 1 mile wide, and $\frac{1}{4}$ mile deep. It would take as many as a thousand molecules laid side by side to make a speck long enough to be seen with the best microscopes.

Evidence for molecular motions in gases. If a little ammonia or any gas of powerful odor is liberated in a closed room, in a very short time one can smell it all over the room, even though the air is still. Facts of this sort lead us to believe that the molecules of the gas must be in continuous and rapid motion. Indeed, we shall soon see that they move with rifle-bullet speeds.

* From a Greek word meaning "to move."

A Real "Twister"

Snapped at Hardtner, Kansas, June 2, 1929, by Ira B. Blackstock. The white spots in the foreground are big hailstones



Albert Einstein (1879–   )

Most creative of living theoretical physicists; developed in 1905 the theory of the Brownian movement and pointed the way thereby to the experimental verification of the molecular and kinetic hypothesis; first set up, also in 1905, the so-called Einstein photoelectric equation, which involves a new conception as to the nature of light, an equation subsequently completely verified experimentally; awarded the Nobel prize in 1921 for this last accomplishment; author of the special theory of relativity in 1905 and of the general theory of relativity in 1914, both of which have had great success in explaining otherwise unexplained phenomena and in predicting new ones

Again, chemists tell us that if two globes, one containing hydrogen and the other carbon-dioxide gas, be connected as in Fig. 60, and the stopcock between them be opened, after a few hours chemical analysis will show that each of the globes contains the two gases in exactly the same proportions — a result which is at first sight very surprising, since carbon-dioxide gas is about twenty-two times as heavy as hydrogen. This mixing of gases in apparent violation of the laws of weight is called *diffusion.*

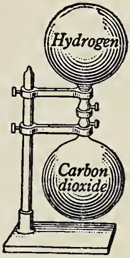


FIG. 60. Illustrating the diffusion of gases

We see, then, that such simple facts as the transference of odors and the diffusion of gases tend to show that the molecules of a gas are not at rest but are continuously moving about.

Molecular motions and the indefinite expansibility of a gas. Perhaps the most striking property which we have found gases to possess is the property of indefinite, or unlimited, expansibility. The existence of this property was demonstrated by the fact that we were able to attain a high degree of exhaustion by means of an air pump. No matter how much air was removed from the bell jar, the remainder at once expanded and filled the entire vessel. The motions of the molecules furnish a thoroughly satisfactory explanation of the phenomenon.

The fact that, however rapidly the piston of the air pump is drawn up, gas always appears to follow it instantly, leads us to the conclusion that the natural velocity possessed by the molecules of gas must be very great.

Molecular motions and gas pressures. How are we to account for the fact that gases exert such pressures as they do against the walls of the vessels which contain them? We have found that in a room at sea level the air presses against the walls with a force of 15 pounds to the square inch. Within a pneumatic truck tire this pressure may amount to as much as 100 pounds, and the steam pressure within the boiler of a

locomotive is often as high as 300 pounds per square inch. Yet in all these cases we may be certain that the molecules of the gas are separated from one another by distances which are large in comparison with the diameters of the molecules: for when we reduce steam to water it shrinks to $\frac{1}{1600}$ of its original volume, and when we reduce air to the liquid form it shrinks to about $\frac{1}{800}$ of its ordinary volume.

The explanation is at once apparent when we reflect upon the *motions* of the molecules. For just as a stream of water particles from a hose exerts a continuous force against a wall on which it strikes, so the blows which the innumerable molecules of a gas strike against the walls of the containing vessel must constitute a continuous force tending to push out these walls. In this way we account for the fact that vessels containing only gas do not collapse under the enormous pressures from the outside.

Explanation of Boyle's law. It was shown in the last chapter that when the density of a gas is doubled, the temperature remaining constant, the pressure is likewise found to double; that when the density is trebled, the pressure is trebled; etc. This, in fact, was the assertion of Boyle's law. Now this is exactly what would be expected if the pressure which a gas exerts against a given surface is caused by blows struck by an enormous number of swiftly moving molecules; for doubling the number of molecules in the given space (that is, doubling the density) would simply double the number of blows which are struck per second against that surface, and hence would double the pressure. The kinetic theory of gases which is here presented accounts in this simple manner for Boyle's law.

Brownian movements and molecular motions. Early in this century it was found possible to demonstrate the existence of molecular motions in gases in a very direct and striking way. Experiments show that very minute oil drops suspended in perfectly stagnant air, instead of being themselves at rest, are ceaselessly dancing about just as though they were alive. In 1913 it was definitely proved that these motions, which

are known as the *Brownian movements* (named from the English botanist Brown, who first discovered them), are the direct result of the bombardment which the droplets receive from the flying molecules of the gas with which they are surrounded; for at a given instant this bombardment is not the same on all sides, and hence the suspended particle, if it is minute enough, is pushed hither and thither according as the bombardment is more intense first in one direction, then in another. While we do not actually see the molecules themselves moving, owing to their small size, we see their bombarding *effect* on the oil particles. There can be no doubt that what the oil drops are here seen to be doing, the molecules themselves are also doing, only in a much more lively way.

Molecular velocities. From the known weight of a cubic centimeter of air under normal conditions, and the known force which it exerts per square centimeter (namely, 1033 grams), it is possible to calculate the velocity which its molecules must possess in order that they may produce this amount of force by their collisions against the walls. The result of the calculation gives to the air molecules under normal conditions a velocity of about 445 meters per second, and it assigns to the hydrogen molecules the enormous speed of 1700 meters (over a mile) per second. The speed of a projectile is seldom greater than 800 meters (2600 feet) per second. It is easy to see, then, since the molecules of gases have such speeds, why air, for example, expands instantly into the space left behind by the rising piston of the air pump, and why any gas always fills completely the vessel which contains it.

Diffusion of gases through porous walls. The following experiment helps to strengthen our belief in the molecular theory:

Close a porous cup of unglazed earthenware with a rubber stopper through which a glass tube passes, as in Fig. 61. Dip the tube into a dish of colored water, and place a jar containing hydrogen over the porous cup; or hold the jar in the position shown in the figure, and

pass illuminating gas into it by means of a rubber tube connected with a gas jet. The rapid passage of bubbles out through the water will show that the gaseous pressure inside the cup is rapidly increasing. Now lift the bell jar so that the hydrogen is removed from the outside. Water will at once begin to rise in the tube, showing that the pressure within the porous cup is now rapidly decreasing.

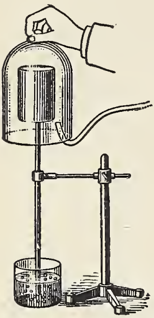


FIG. 61. Diffusion of hydrogen through a porous cup

The explanation is as follows: We have learned that the molecules of hydrogen have about four times the velocity of the molecules of air. Therefore, if there are as many hydrogen molecules per cubic centimeter *outside* the cup as there are air molecules per cubic centimeter *inside*, the hydrogen molecules will strike the outside of the wall four times as frequently as the air molecules will strike the inside. Therefore in a given time the number of hydrogen molecules which pass into the interior of the cup through the little holes in the porous material is four times as great as the number of air particles which pass out; hence the pressure within increases. When the bell jar is removed, the hydrogen which has passed inside begins to pass out faster than the outside air passes in, and hence the inside pressure is diminished.

If, instead of the porous cup, a plant or animal membrane is used, the diffusion process is called *osmosis*. Osmosis plays an important part in plant and animal life. It is the means by which the oxygen taken into the lungs passes into the blood stream.

Molecular Motions in Liquids

Molecular motions in liquids and evaporation. Evidence that the molecules of liquids as well as those of gases are in a state of perpetual motion is found, first, in the familiar facts of evaporation.

We know that the molecules of a liquid in an open vessel are continually passing off into the space above, since it is only a matter of time until the liquid completely disappears and the vessel becomes dry. Now it is hard to imagine a way in which the molecules of a liquid thus pass out of the liquid into the space above, unless these molecules, while in the liquid condition, are in motion. As soon, however, as such a motion is assumed, the facts of evaporation are easily explained. For it is to be expected that in the jostlings and collisions of rapidly moving liquid molecules an occasional molecule will acquire a velocity much greater than the average. This molecule may then, because of the unusual speed of its motion, break away from the attraction of its neighbors (see page 134) and fly off into the space above. This, we believe, is how the process of evaporation goes on from the surface of any liquid.

[**Molecular motions and the diffusion of liquids.** Diffusion occurs in liquids, as well as in gases, and is a convincing argument for believing that there is molecular motion in liquids also.

[Pulverize and dissolve in water a few lumps of blue litmus. Half fill a tall glass cylinder with part of this water and add a few drops of ammonia to make it alkaline. Turn the remainder of the litmus solution red by adding 1 or 2 cm^3 of nitric acid. Slightly cool; then introduce this acidulated water into the bottom of the jar through a thistle tube (Fig. 62). In the course of a few hours, even though the jar is kept perfectly quiet, the red color will be found to have spread considerably toward the top, showing that the acid molecules have gradually found their way up. Diffusion mixes the two liquids, but very slowly, owing to the constant collisions of the molecules with one another. Each molecule therefore moves over a very irregular path in its wanderings.

Fig. 62. Diffusion of liquids

[Certainly, then, the molecules of a liquid must have the power of independent motion. Indeed, every one of the

arguments for molecular motions in gases applies with equal force to liquids. Even the Brownian movements can be seen in liquids, though they are here so small that high-power microscopes must be used to make them visible. If a small amount of insoluble carmine is ground into a few drops of water, these movements may be seen with a microscope magnifying four hundred or more diameters.

Molecular Motions in Solids

Molecular motions and the diffusion of solids. It is more or less easy to believe that gases and liquids are made up of tiny molecules comparatively far apart and in motion with tremendous velocities. It is more difficult to believe that this is true of solids also. Yet it has been demonstrated that if a layer of lead is placed upon a layer of gold, molecules of gold may in time be detected throughout the whole mass of the lead. This diffusion of solids into one another at ordinary temperatures has been shown only for these two metals, but at higher temperatures (for example, 500° C.) all the metals show this same characteristic to a surprising degree. We know that molecules break away from the surface of certain solids, such as camphor and naphthalene "moth balls," because the odor of these substances may be detected at a considerable distance.

The evidence for the existence of molecular motions in solids is, then, no less strong than in the case of liquids.

Motions in solids, gases, and liquids. The same kind of matter may exist in three different forms, or states. Water, for instance, may be frozen until it becomes a solid (ice), or it may be heated until it changes into the gaseous form of steam. In all three states its composition is the same, namely two parts of hydrogen and one of oxygen; but its physical properties are different. The molecules are the same, but in the change of state we find a difference in their relative positions and in their kind and freedom of motion.

Thus in the solid state it is probable that the molecules

oscillate with great rapidity about certain fixed points, always being held by the attractions of their neighbors — that is, by the *cohesive forces* (see page 133) — in very nearly the same positions with reference to other molecules in the body. In rare instances, however, as the facts of diffusion show, a molecule breaks away from its constraints. In *liquids*, on the other hand, although the molecules are, in general, as close together as in solids, they slip about with perfect ease over one another and thus have no fixed positions. This seems true, since liquids adjust themselves readily to the shape of the containing vessel. In *gases* the molecules are comparatively far apart, as is evident from the fact that a cubic centimeter of water increases to about 1600 cubic centimeters when it is changed into steam; and, furthermore, they exert almost no cohesive force upon one another, as is shown by the indefinite expansibility of gases.

Summary. **The kinetic theory of the constitution of matter states that all matter is composed of tiny particles called molecules, relatively far apart and moving at extremely high speeds.**

Evidence of molecular motion (the kinetic theory of matter) is found in diffusion, in the indefinite expansibility of gases, in Brownian movements, and in the evaporation of liquids and solids.

Boyle's law is explained by the assumption that at a given temperature the pressure is determined by the number of molecular blows per second on unit area.

The rate of diffusion of a light gas is greater than that of a heavy one because of the greater velocity of its less massive molecules.

QUESTIONS AND PROBLEMS

A

1. Account for the fact that if ammonia water is spilled in a room, the odor of the ammonia gas may be quickly detected in all parts of the room.

2. Why does not the tendency to unlimited expansion cause the atmosphere to leave the earth?

3. Why does a confined body of gas exert pressure inversely proportional to its volume?

4. A lump of copper sulfate placed at the bottom of a graduate filled with water will dissolve and very slowly pass upward, although a copper-sulfate molecule is many times heavier than a water molecule. Explain.

B

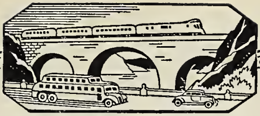
1. What is the density of the air within an automobile tire that is inflated to a *gauge* pressure of 30 lb/in.^{2}? (Take 1 atmosphere = 15 lb/in.^{2})

2. A liter of air at a pressure of 76 cm is compressed so as to occupy 400 cm^3. What is the pressure against the walls of the containing vessel?

3. Salt is heavier than water. Why does not all the salt in a mixture of salt and water settle to the bottom?

4. If a vessel with a small leak is filled with hydrogen at a pressure of 2 atmospheres, the pressure falls to 1 atmosphere about four times as fast as when the same experiment is tried with air. Can you see a reason for this?

5. (*a*) Find the pressure to which the diver was subjected who descended to a depth of 304 ft. (*b*) Find the density of the air in his suit, the density at the surface being .00128 g/cm^3 and the temperature being assumed to remain constant. Take the pressure at the surface as 30 in.



UNIT TWO

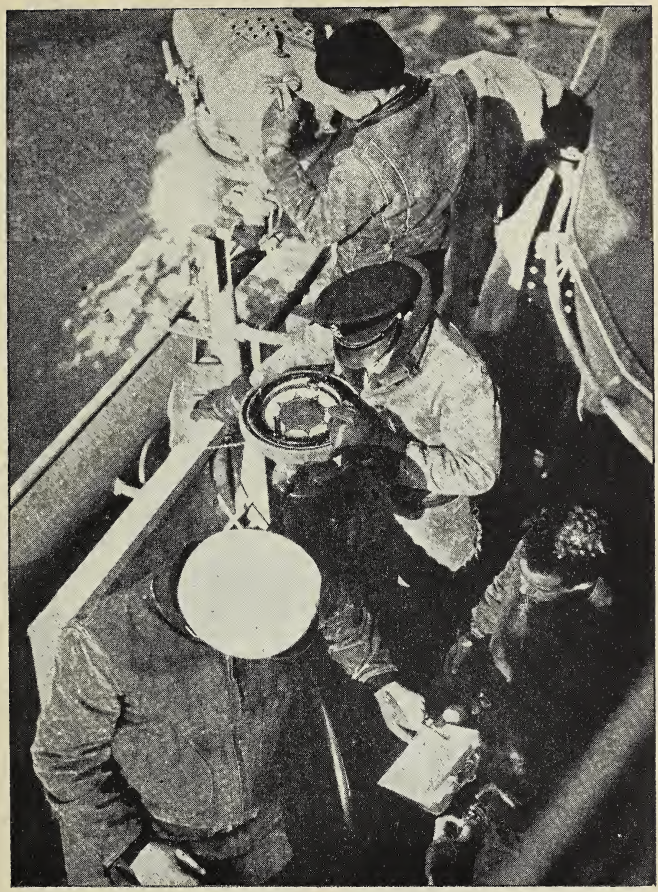
The Laws of Force and Motion

Galileo and Newton are the two men who have the best right to be called the founders of modern science. Newton was born in 1642, the same year in which Galileo died. Galileo has been called the first of the moderns. He was the first to grasp the full significance of the experimental method and the first to apply it consistently in his now famous study of the laws of falling bodies. In those studies he laid the foundations upon which the whole of modern physical science has been built and a very large part of all science

It was definitely with the aid of Galileo's results that Newton, in the next century, discovered the law of gravitation, which for the first time made it possible to understand and indeed to predict, for years ahead, the motions of the heavenly bodies. Newton's three laws of motion also, universally recognized as the basis of all the laws discussed in this unit, grew directly out of Galileo's researches. In fact, not a single steam engine, automobile, dynamo, airplane, or power machine of any kind can be built today without using the formula that Galileo discovered and Newton formulated, namely, Force $=$ mass $\times$ acceleration.

Even more important than any material changes is the influence of the work of Galileo and Newton in bringing into the world a significant change in human outlook. Through all primitive thinking, and some of it not so primitive, nature was regarded as essentially capricious. Things happened because the god of the

mountain, the forest, the river, or the sea willed to have them happen, and that god was usually endowed with practically all man's frailties and caprices. Galileo in establishing the laws of force and motion assumed *the principle of uniformity* and formulated *regularities*, or laws, which made the prediction of astronomical events and of some terrestrial events a possibility. The continued and ever increasing success of these predictions soon began inevitably to change man's thinking about the fundamental nature of the universe. The gods of caprice and whim began to be replaced in human thinking by a God who rules through law; a universe which was not worth studying, because it could not be counted upon, began to be replaced by a universe which is thought of as dependable and to some extent understandable, and even controllable by man. With the advent of this idea man began to be less timid in the face of nature, less superstitious, less prone to depend upon charms, incantations, hunches, witch doctors — no longer merely a plaything in the hands either of blind fate or of a capricious deity, but himself a vital agent in the march of things. The philosopher Professor Whitehead of Harvard University calls this change "the most intimate change in outlook the human race had yet encountered." It is, then, the fundamental experiments that were first made in one of the most significant periods in human history that are to be studied in this second unit of physics.



Blinkers

On the bridge of this destroyer messages are being received and sent by the use of a blinker. In such signaling, short and long flashes correspond to the dots and dashes of the International Morse Code. The rate of such signaling is usually eight words per minute. (Courtesy of U. S. Navy)

The Mark Twain Zephyr

The *Zephyr* was the first Diesel-powered streamlined railway train built in America (1934). On May 26, 1934, this train established a new long-distance nonstop world record when it ran from Denver to Chicago, 1015 miles, in 785 minutes, with a top speed of 112.5 miles per hour. By October, 1935, there were four *Zephyrs* running on regular service on the Burlington Lines, each of them powered with a two-cycle, eight-in-line, 660-horsepower Diesel engine

CHAPTER V

Force and Motion

Definition and Measurement of Force

Distinction between a gram of mass and a gram of force. Much of the subject matter of physics has to do with the action of forces on matter. We think of a force as a push or a pull on a body, tending to move it, or to change its rate or direction of motion if it is already moving. Thus, if a gram of mass is held in the outstretched hand, a downward pull upon the hand is felt. If the mass is 50,000 grams instead of 1, this pull is so great that the hand cannot be held in place. The cause of this pull we assume to be an attractive force which the earth exerts on the matter held in the hand, and *we define the gram of force as the amount of the earth's pull at its surface upon 1 gram of mass.*

Unfortunately in ordinary conversation we often fail altogether to distinguish between the idea of mass and that of force, and we use the same word, *gram*, to mean sometimes *a certain amount of matter* and at other times *the pull of the earth upon this amount of matter*. That the two ideas are wholly distinct, however, is evident, since the amount of matter in a body is always the same, wherever the body is in the universe, whereas the pull of the earth upon that amount of matter decreases as we recede from the earth's surface. It will help to avoid confusion if we reserve the simple term *gram* to denote exclusively an amount of matter (that is, a mass) and use the full expression *gram of force* wherever we have in mind the pull of the earth upon this mass.

Method of measuring forces. When we wish to compare accurately the pulls exerted by the earth upon different

masses, we find the muscular sense a very untrustworthy guide. An accurate method, however, of comparing these pulls is that furnished by the stretch produced in a spiral spring. Thus the pull of the earth upon a gram of mass at its surface will stretch a given spring a given distance, *ab* (Fig. 63); the pull of the earth upon 2 grams of mass is found to stretch the spring a larger distance, *ac*; upon 3 grams, a still larger distance, *ad*; and so on. In order to graduate (mark off) a spring balance (Fig. 64) so that it will thenceforth measure the values of any pulls exerted upon it, no matter how these pulls may arise, we have only to place a fixed surface behind the pointer and make lines upon it corresponding to the points to which it is stretched by the pull of the earth upon different masses. For example, if a man stretches the spring so that the pointer is opposite the mark corresponding to the pull of the earth upon 2 grams of mass, we say that he exerts 2 grams of force; if he stretches it the distance corresponding to the pull of the earth upon 3 grams of mass, he exerts 3 grams of force; and so on. *The spring balance thus becomes an instrument for measuring forces.*

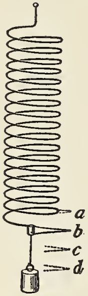


Fig. 63. Method of measuring forces

Fig. 64. The spring balance

The gram of force varies slightly in different localities. With the spring balance it is easy to verify the statement made above, that the force of the earth's pull decreases as we recede from the earth's surface; for upon a high mountain the stretch produced by the weight of a given mass is, indeed, found to be slightly less than at sea level. Furthermore, if the balance is carried from point to point over the earth's surface, the stretch is still found to vary slightly. For example, at Chicago it is about one part in 1000 less than it is at Paris, and near the equator it is five

parts in 1000 less than it is near the pole. This is due in part to the earth's rotation (see page 122) and in part to the fact that the earth is not a perfect sphere and that in going from the equator toward the pole we are coming nearer and nearer to the center of the earth. We see that *the weight of 1 gram of mass is not an absolutely definite unit of force.* For certain scientific purposes, therefore, it has been found useful to set up a so-called *absolute* unit of force, which does not change with change of position on the earth's surface. (See page 125.)

Composition and Resolution of Forces *

Graphic representation of force. A force is completely described when its *magnitude* (size), its *direction*, and the *point at which it is applied* are given. Since the three characteristics of a straight line are its *length*, its *direction*, and the *point at which it starts*, it is obviously possible to represent forces by means of straight lines. Thus, if we wish to represent the fact that a force of 8 pounds, acting in an easterly direction, is applied at the point A (Fig. 65), we draw a line 8 units long, beginning at the point A and extending to the right (as on a map). The length, the direction, and the starting point of this line represent the magnitude, the direction, and the point of application, respectively, of the force.

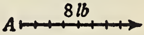


FIG. 65. Graphic representation of a single force

Resultant of two forces acting in the same line. If two boys who had been carrying a bucket of water between them allowed a man to carry it alone, the man's force would be called the *resultant* of the two forces exerted by the boys. *The resultant of two or more forces is defined as that single force which when substituted for the others will produce the same effect on a body as was produced by the combined action of the two or more forces.*

* Laboratory experiments on parallel and concurrent forces should accompany this discussion. See, for example, Experiments 10 and 11 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

If two spring balances are attached to a small ring and pulled in the same direction until one registers 10 grams of force and the other 5, it will be found that a third spring balance attached to the same point and pulled in the opposite direction will register exactly 15 grams when there is equilibrium; that is, *the resultant of two parallel forces acting in the same direction is equal to the sum of the two forces.*

Similarly *the resultant of two oppositely directed forces applied at the same point is equal to the difference between them, and its direction is that of the greater force.*

Equilibrant. In the last experiment the pull in the spring balance which registered 15 grams was not the resultant of the 5-gram and 10-gram forces; it was rather a force equal and opposite to that resultant. Such a force is called an *equilibrant. The equilibrant of a force or forces is that single force which will just balance these forces, that is, prevent the motion which the given forces tend to produce.* It is equal and opposite to the resultant and has the same point of application.

Resultant of forces acting at an angle (concurrent forces). A bather in attempting to swim across a swiftly flowing river finds very often that he has landed on the other side a considerable distance below the point he started from. Two forces have been acting simultaneously upon him: his own muscular force, which attempted to propel him directly across the river, and the force of the current, which tended to move him directly downstream. Let *AB* (Fig. 66) represent the muscular force, and *AC* represent the force of the current urging him downstream. Then his motion must be the same as though some *single* force acted on him somewhere between *AC* and *AB*. If a body moves under the action of two equal forces, it may be seen from symmetry that it must move along a line midway between *AC* and *AB*, that is, along the line *AR*. Therefore this line indicates the *direction* as well as the point of application of the resultant of the forces *AC* and *AB*.

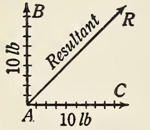


FIG. 66. Direction of resultant of two equal forces at right angles

If the two forces are not equal, as in Fig. 67, then the resultant will lie nearer the larger force. The following experiment will show the relation between the two forces and their resultant:

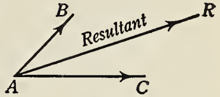


FIG. 67. The resultant lies nearer the larger force

Hang the rings of two spring balances over nails *B* and *C* in the rail at the top of the blackboard (Fig. 68), and tie a weight *W* near the middle of the string joining the hooks of the two balances. The weight *W* is not supported by the pull of the balance *E* or by that of *F*; it is supported by their resultant, which evidently must act vertically upward, since the only *single* force capable of supporting the weight *W* is one that is equal and opposite to *W*. Draw the lines *OA* and *OD* upon the blackboard behind the string, and upon these lines lay off the distances *Oa* and *Ob*, which contain as many units of length as there are units of force indicated by the balances *E* and *F* respectively. Similarly on a vertical line from *O* lay off the exact distance *OR* required to represent the force that supports the weight. This, as noted above, represents the resultant. Now construct a parallelogram upon *Oa* and *Ob* as sides. The line *OR* already drawn will be found to be the diagonal.

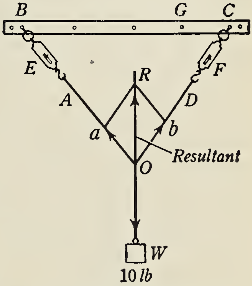


FIG. 68. Experimental proof of parallelogram law

Hence, *to find graphically the resultant of two concurrent forces,* (1) *represent the concurrent forces as adjacent sides of a parallelogram,* (2) *complete the parallelogram, and* (3) *draw a diagonal from the point of application. This diagonal represents the point of application, the direction, and the magnitude of the resultant.*

This process of finding the resultant of two or more known forces is called the *composition of forces.* It is sometimes necessary to reverse this process, that is, to find the component forces, the resultant being known. This process is called the *resolution of forces.* If the angle *AOD* is a right angle, it is possible to find the numerical value of the resultant

by geometry. ($\overline{OR}^2 = \overline{Oa}^2 + \overline{Ob}^2$.) If the angle is *not* a right angle, the student of trigonometry will have a formula for its solution.

Component of a force. It often happens that a force cannot be applied in the direction in which the effect is desired, but has to be applied at an angle. A boy pushing a lawn-mower (Fig. 69) cannot conveniently exert his force directly in the direction in which he wishes the mower to go, but must push in the direction OR, indicated by the handle. Part of this force is trying to push the mower into the ground, and only part is left to produce horizontal motion. The value of the single force which, acting in the direction OA, will produce the same motion of the mower as is produced by OR is called the *component* of OR in the direction OA. Similarly the value of the single force which, acting in the direction OB, will give the same pressure against the ground as is produced by the force OR is called the component of OR in the direction OB. In a word, *the component of a force in a given direction is the effective value of the force in that direction.*

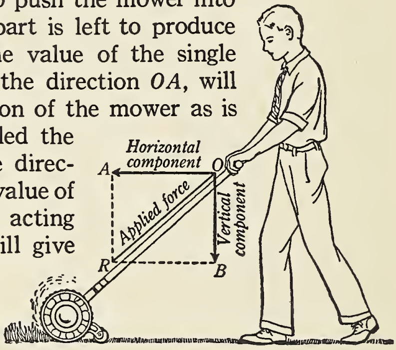


FIG. 69

Magnitude of the component of a force in a given direction. Since, from the definition of *component* just given, the two forces, one to be applied in the direction OA and the other in the direction OB, are together to be exactly equivalent to OR in their effect on the mower, their magnitudes must be represented by the sides of a parallelogram of which OR is the diagonal. For on page 88 it was shown that if any one force is to have the same effect upon a body as two forces acting simultaneously, it must be represented by the diagonal of a parallelogram the sides of which represent the two forces. Hence, conversely, if two forces are to be equivalent in their

joint effect to a single force, they must be represented by the sides of the parallelogram of which the diagonal represents the single force. Hence the following rule: *To find the component of a force in any given direction, represent the force by a line; then, using the line as a diagonal, construct upon it a parallelogram the sides of which are, respectively, parallel and perpendicular to the direction of the required component. The length of the side which is parallel to the given direction represents the magnitude of the component which is sought.* Thus in Fig. 69 the line OA completely represents the component of OR in the direction OA, and the line OB represents the component of OR in the direction OB.

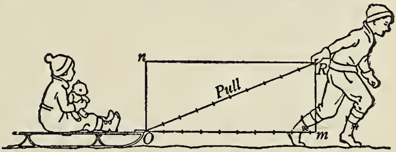


FIG. 70. Horizontal component of pull on a sled

Again, when a boy pulls on a sled with a force of 10 pounds in the direction OR (Fig. 70), the force with which the sled is urged forward is represented by the length of Om, which is seen to be but 9.3 pounds instead of 10 pounds. The component which tends to lift the sled is represented by On.

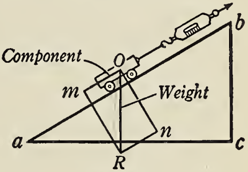


FIG. 71. Component of weight parallel to an inclined plane

These conclusions may be tested experimentally. If a small car is placed on a *horizontal* board, the whole weight of the car represents a force which is trying to break the board. There is, however, no tendency for the car to move along the board, or, in the language which we have just learned, there is no *horizontal* component of this force of gravity. As one end of the board is raised, however (Fig. 71), then a component, Om, of gravity begins to make the car move down the board, unless it is held back by some force; in this case the force is the pull of the spring balance.

If the board is raised still more, the component Om becomes greater and greater, and On less, until finally, when the board is in a vertical position, the whole weight of the car acts directly downward and parallel to the board, and no component of it tends to break the board.

Now place the car on the board tilted so that the height bc is equal to half its length ab. The force acting on the car is the weight of the car, and its direction is downward. Let this force be represented by the line OR. Then, by the construction of the preceding page, Fig. 71, the line Om will represent the value of the force which is pulling the car down the plane, and the line On the value of the force which is producing pressure against the plane. Now, since the triangle ROm is similar to the triangle abc (for $\angle mOR = \angle abc$, $\angle RmO = \angle acb$, and $\angle ORm = \angle bac$), we have

$$\frac{Om}{OR} = \frac{bc}{ab};$$

that is, in this case, since bc is equal to half of ab, Om is half of OR. Therefore the force which is necessary to prevent the car from moving down the plane should be equal to half its weight. To test this conclusion weigh the car on the spring balance and then place it on the plane in the manner shown in the figure. The pull indicated by the balance will be found to be half the weight of the car, if there is no friction.

The equation $Om/OR = bc/ab$ gives us the following rule for finding the force necessary to prevent a body from moving down an inclined plane: *The force F which must be applied to a body to hold it in place upon an inclined plane bears the same ratio to the weight W of the body as the height h of the plane bears to its length l, or*

$$\frac{F}{W} = \frac{h}{l}.$$

Component of gravity effective in producing the motion of the pendulum. When a pendulum is drawn aside from its position of rest (Fig. 72), the force acting on the bob is its weight, and the direction of this force is vertical. Represent the force by the line $O'R$. The component of this force in the

direction in which the bob is free to move is $O'n$ (or $O''n'$), and the component at right angles to this direction is $O'm$ (or $O''m'$). The second component simply produces stretch in the string and pressure upon the point of suspension. The first component is alone responsible for the motion of the bob. A study of the figure shows that this component becomes larger and larger the greater the displacement of the bob. When the bob is directly beneath the point of support, the component producing motion is zero. Hence a pendulum can be permanently at rest only when its bob is directly beneath the point of suspension.*

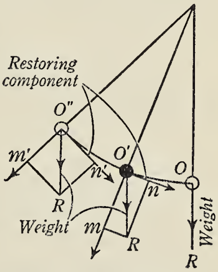


FIG. 72. Force acting on displaced pendulum

Laws of the pendulum. The pendulum is commonly used in the pendulum clock for the measurement of time. It is said that Galileo first studied the pendulum by counting the vibrations of a swinging chandelier in the cathedral in Pisa, Italy, using his pulse to time the swings. To study the laws of the pendulum it is wise first to define three terms, *amplitude*, *period*, and *frequency*. These terms are important in the later study of wave motion in electricity, sound, and light. A single vibration is the swing from one side of the arc to the other; the *amplitude* is the distance OO'' (Fig. 72), that is, the greatest deviation from the position of rest; the *period* is the time in seconds that it takes to make one complete vibration (over and back); and the *frequency* is the number of complete vibrations that it makes in one second.

It can easily be seen that the period T of the pendulum is the reciprocal of its frequency n, or

$$T = \frac{1}{n}.$$

* It is recommended that the study of the laws of the pendulum be introduced into the laboratory work at about this point (see Experiment 12 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis).

The laws of the pendulum are obtained from the following experiments:

If two pendulums of exactly the same length (about 1 m), one having a bob of lead and the other a bob of steel or wood, are pulled back and released at the same instant, and their periods observed, we shall obtain the first law of the pendulum; namely,

1. *The periods of pendulums of the same length swinging through short arcs are independent of the mass and the material of the bobs.*

Set the two pendulums swinging through arcs of lengths 2 cm and 5 cm respectively. We shall thus find the second law of the pendulum; namely,

2. *The period of a pendulum swinging through a short arc is independent of the amplitude of the arc.*

Let pendulums one fourth and one ninth as long as the ones used before be swung with it. The long pendulum will be found to make only one vibration while the others are making two and three respectively. Therefore the third law of the pendulum is

3. *The periods of pendulums are directly proportional to the square roots of their lengths.*

Since $T = \frac{1}{n}$, we have the fourth law of the pendulum; namely,

4. *The frequencies of pendulums are inversely proportional to the square roots of their lengths.*

Summary. **A gram of mass is a definite quantity of matter which is the same everywhere; whereas a gram of force, which is the pull of the earth at sea level upon a gram of mass, varies slightly with position on the earth.**

The resultant of a set of forces is that single force which will produce the same effect upon a body as is produced by the joint action of the set of forces. The rules for finding the resultant have been found (pp. 87–89).

The component of a force in a given direction is the effective value of the force in that direction. Rules for finding the component have been found (p. 90).

A pendulum swings because of the component of its weight in the direction of its motion.

The length laws of the pendulum expressed as formulas are

$$\frac{T_1}{T_2}=\frac{\sqrt{l_1}}{\sqrt{l_2}},$$

$$\frac{n_1}{n_2}=\frac{\sqrt{l_2}}{\sqrt{l_1}}.$$

QUESTIONS AND PROBLEMS

[Solve the concurrent-force problems by plotting to scale (the larger, the more accurate the solution) and then check by mathematics if possible.]

A

1. Two forces of 100 lb and 75 lb respectively are acting on a body at a point. In what directions would they have to act (*a*) to have the maximum resultant? (*b*) to have the minimum resultant?

2. A boy can row a boat 5 mi/hr in still water. On a river which flows 2 mi/hr, how fast would his boat move (*a*) downstream? (*b*) upstream?

3. The wind drives a steamer east with a force which would carry it 12 mi/hr, and its propeller is driving it south with a force which would carry it 15 mi/hr. What distance will it actually travel in an hour? Draw a diagram to represent the exact path.

4. Represent graphically a force of 30 lb acting southeast and a force of 40 lb acting southwest at the same point. (*a*) What will be the magnitude of the resultant? (*b*) What will be its approximate direction?

5. An airplane which flies in still air with a velocity of 120 mi/hr is flying in a wind whose velocity is 60 mi/hr toward the east. Find the actual velocity of the airplane and the direction of its motion when headed (*a*) north; (*b*) east; (*c*) south; (*d*) west.

6. A barge is anchored in a river during a storm. If the wind acts eastward on it with a force of 3000 lb and the tide acts northward on it with a force of 4000 lb, what is the direction and the magnitude of the equilibrant (that is, the horizontal component of the pull of the anchor cable upon the barge)?

7. A cord 10 ft long has its ends fastened 8 ft apart on a ceiling and supports a weight of 20 lb from its middle point. Find the tension (pull) on each of the halves of the cord.

8. A horizontal pull of 24 lb draws a loaded sled on level snow. If the sled rope is 5 ft long, how much pull on the rope is required to draw the sled when one end of the rope is (*a*) 3 ft higher than the other? (*b*) 4 ft higher than the other?

9. A pendulum makes 10 vibrations in 30 sec. Find (*a*) its period and (*b*) its frequency. (*c*) From these two answers show that

$$T = \frac{1}{n}.$$

B

1. A canal boat and the engine towing it move in parallel paths which are 50 ft apart. The tow rope is 130 ft long, and the force (effort) applied to the end of the rope is 1300 lb. Find what component of the 1300 lb acts parallel to the path of the boat.

2. A child weighing 100 lb sits in a swing. The swing is drawn aside and held in equilibrium by a horizontal force of 40 lb. Find the tension on each of the two ropes of the swing.

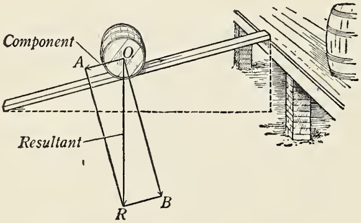


FIG. 73. Force necessary to prevent a barrel from rolling down an inclined plane

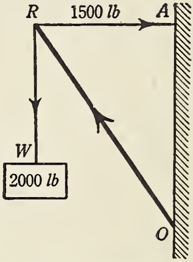


FIG. 74. Crane boom

3. If the barrel of Fig. 73 weighs 200 lb, with what force must a man push parallel to the skid and through the center of the barrel to keep the barrel in place if the skid is 9 ft long and the platform 3 ft high?

4. Fig. 74 represents a simplified diagram of a crane boom, a device used industrially to lift huge weights. Find the push which the crane arm *RO* must exert in helping to support the weight *W*.

5. If a clock gains time, what change should be made in its pendulum? Why?

6. Fig. 75 represents the pendulum and escapement of a clock. The escapement wheel D is urged in the direction of the arrow by the clock weights or spring. The slight pushes communicated by the teeth of the wheel keep the pendulum from dying down. Show how the length of the pendulum controls the rate of the clock.

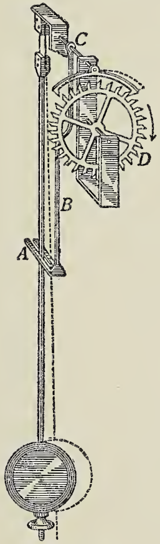


FIG. 75

7. A picture weighing 20 lb hangs upon a cord whose parts make an angle of 120° with each other. Find the tension on each part of the cord.

8. If the parts of the cord in Problem 7 had made an angle of 90°, what would have been the tension on each part of the cord?

9. Three boys, weighing each 100 lb, hang from a horizontal ladder, as shown

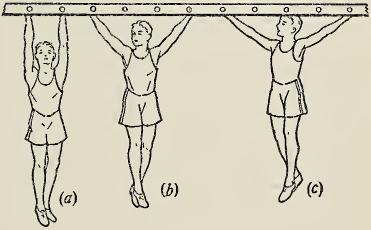


FIG. 76

in Fig. 76: (*a*) arms parallel; (*b*) arms at 90°; (*c*) arms at 120°. Find in each case how much the arms pull to support the weight of the boy.

10. The anchor rope of a kite balloon makes an angle of 60° with the surface of the earth. If the lifting force of the balloon is 1000 lb, find (*a*) the pull of the balloon on the rope and (*b*) the horizontal force of the wind against the balloon.

11. A cake of ice weighing 200 lb is held at rest upon an inclined plane 12 ft long and 3 ft high. (*a*) By the resolution-and-proportion

method find the component of its weight that tends to make the ice slide down the incline. (*b*) With what force must one push to keep the ice at rest? (*c*) How great is the component that tends to break the incline?

12. A boy pulls a loaded sled weighing 200 lb up a hill which rises 1 ft in 5 measured along the slope. Friction being neglected, how much force must he exert?

13. A pendulum that makes a single swing per second in New York City is 99.3 cm, or 39.1 in., long. Account for the fact that a seconds pendulum at the equator is 39 in. long, whereas at the poles it is 39.2 in. long.

14. How long is a pendulum whose period is (*a*) 3 sec? (*b*) 2 sec? (*c*) $\frac{1}{2}$ sec? (*d*) $\frac{1}{3}$ sec?

15. The lengths of 5 pendulums are in the ratio of $1:4:9:\frac{1}{4}:\frac{1}{9}$. What is the ratio of their periods?

16. A man was let down over a cliff on a rope 500 ft long. What was his period as a pendulum?

Gravitation

Newton's law of universal gravitation. One of the most common forces which we become familiar with in early childhood, and have to deal with throughout life, is the force of gravitation. In order to account for the fact that the earth pulls bodies toward itself, and also that the moon and the planets are held in their respective orbits about the earth and the sun, Sir Isaac Newton (1642–1727) (see opposite page 98) first announced the law which is now known as the law of universal gravitation. This law asserts first that *every body in the universe attracts every other body with a force which varies inversely as the square of the distance between the two bodies.* This means that if the distance between the two bodies considered is doubled, the force will become only one fourth as great; if the distance is made three, four, or five times as great, the force will be reduced to one ninth, one sixteenth, or one twenty-fifth of its original value; etc.

The law further asserts that if the distance between two bodies remains the same, *the force with which one body attracts*

Sir Isaac Newton (1642–1727)

English mathematician and physicist; "prince of philosophers"; professor of mathematics at Cambridge University; formulated the law of gravitation; discovered the binomial theorem; invented the method of the calculus; announced the three laws of motion which have become the basis of the science of mechanics; made important discoveries in light; is the author of the celebrated *Principia* (*Principles of Natural Philosophy*), published in 1687

The World's Greatest Suspension Bridge, at the Golden Gate, San Francisco; Channel Span 4200 Feet

the other is proportional to the product of the masses of the two bodies. Thus we know that the earth attracts 3 cubic centimeters of water with three times as much force as it attracts 1; that is, with a force of 3 grams. We know also, from the facts of astronomy, that if the mass of the earth were doubled, its diameter remaining the same, it would attract 3 cubic centimeters of water with twice as much force as it does at present; that is, with a force of 6 grams. (Multiplying the mass of one of the attracting bodies by 3 and that of the other body by 2 multiplies the forces of attraction by 3×2, or 6.)

It is interesting to note that the gravitational pull of the moon is the chief cause of the ocean tides, which occur twice daily.

In brief, then, Newton's law of universal gravitation is as follows: *Any two bodies in the universe attract each other with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.*

This attraction is extremely small between ordinary bodies. Thus two masses of 1 gram each at a distance apart of 1 centimeter attract each other with a force of approximately $\frac{1}{15,000,000,000}$ gram. The masses of the sun and the earth are so great that, even though 93,000,000 miles apart, they attract each other with a force of about 4,000,000,000,000,000,000 tons. A solid bar of high-grade steel 93,000,000 miles long and 5000 miles in diameter would be needed to replace gravitation in holding the earth and the sun together. A body weighing 100 pounds on the earth would weigh about 2700 pounds on the sun. A freely falling body on the earth drops 16 feet the first second; on the sun it would fall 27 times as far in the first second, or 432 feet. On the moon we should weigh $\frac{1}{6}$ of what we do on the earth; we could jump 6 times as high and should fall $\frac{1}{6}$ as far in a given time.

Distinction between mass and weight. The particular gravitational attraction between the earth and a body at or near its surface is called the weight of that body. It is measured in units of force, such as grams of force or pounds of force.

The mass of such a body is the amount, or quantity, of material in it, and is measured in grams or pounds. (See the footnote on page 19 and see page 25.)

Variation of the force of gravity with distance above the earth's surface. If a body is spherical in shape and of uniform density, it attracts external bodies with the same force as though its mass were concentrated at its center. Since, therefore, the distance from the surface to the center of the earth is about 4000 miles, we learn from Newton's law that the earth's pull upon a body 4000 miles above its surface is but one fourth as much as it would be at the surface, the effective distances apart having been doubled.

It will be seen, then, that if a body is raised a few feet or even a few miles above the earth's surface, the decrease in its weight must be a very small quantity, for the reason that a few feet or a few miles is a small distance compared with 4000 miles. As a matter of fact, at the top of a mountain 4 miles high 1000 grams of mass is attracted by the earth with 998 grams of force instead of 1000 grams, and we say that it weighs 998 grams instead of 1000 grams.

Center of gravity. From the law of universal gravitation it follows that every particle of a body upon the earth's surface is pulled toward the earth. It is evident that the sum of all these little pulls on the particles of which the body is composed must be equal to the total pull of the earth upon the body. Now it is always possible to find one single point in a body at which a single force, equal in magnitude to the weight of the body and directed upward, can be applied so that the body will remain at rest (that is, be balanced) in whatever position it is placed. This point is called the *center of gravity* of the body. Since this force counteracts entirely the earth's pull upon the body, it must be equal and opposite to the resultant of all the small forces which gravity is exerting upon the different particles of the body. Hence the center of gravity may be defined as *the point of application of the resultant of all the little downward forces of gravity acting upon the parts of the body*; that is, *the center of gravity of a body is*

the point at which the entire weight of the body may be considered as concentrated. The earth's attraction for a body is therefore always considered not as a multitude of little forces but as one single force F (Fig. 77) equal to the pull of gravity upon the body and applied at its center of gravity G. It is evident, then, that *under the influence of the earth's pull every body tends to assume the position in which its center of gravity is as low as possible.*

FIG. 77. Center of gravity of an irregular body

Method of finding center of gravity experimentally. From the preceding definition it will be seen that the most direct way of finding the center of gravity of any flat body, like that shown in Fig. 78, is to find the point upon which it will balance.

Balance an irregular sheet of zinc or stiff cardboard on the point of a pencil or the head of a pin. Punch a small hole through the zinc at the point of balance and thrust a needle through this hole. When the needle is held horizontally, the zinc will be found to remain at rest, no matter in what position it is turned.

To illustrate another means of finding the center of gravity of the zinc or cardboard, support it by a pin stuck through a hole near its edge — for example, at b (Fig. 78). Hang a plumb line from the pin, and draw a line bn through b on the surface of the zinc or cardboard parallel to and directly behind the plumb line. Hang the zinc or cardboard from another point, a, and draw another line, am, in a similar way. The zinc or cardboard will be found to balance upon the point of intersection of the lines bn and am.

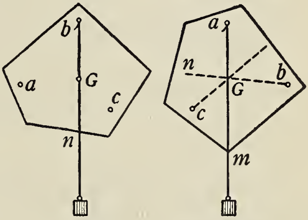


FIG. 78. Locating center of gravity

Since the attraction of the earth for a body may be considered as a single force applied at the center of gravity, a suspended body (for example, the sheet of zinc or cardboard)

can remain at rest only when the center of gravity is directly *beneath* the point of support. It must therefore lie *somewhere* on the line *am*. For the same reason it must lie on the line *bn*. But the only point of the body which lies on both these lines is their point of intersection *G*. *The point of intersection of any two vertical lines dropped through two different points of suspension locates the center of gravity of a body.*

Stable equilibrium. A body is said to be in *stable equilibrium* if it tends to return to its original position when it is very slightly tipped, or rotated, out of that position. A

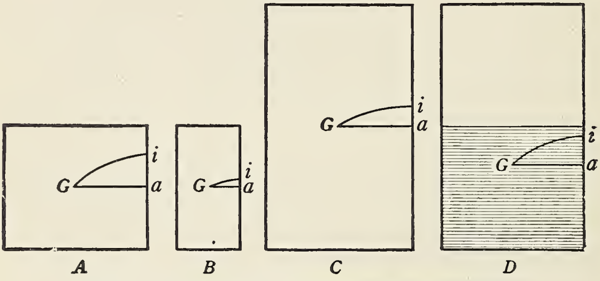


FIG. 79. Illustration of varying degrees of stability

pendulum, a chair, a cube resting on its side, a cone resting on its base, and a boat floating quietly in still water are all illustrations.

In general, *a body is in stable equilibrium whenever a slight tipping tends to raise its center of gravity.* Thus in Fig. 79 all the bodies *A*, *B*, *C*, *D* are in stable equilibrium; for in order to overturn any one of them its center of gravity *G* must be raised through the height *ai*. If the weights are equal, that one will be most stable for which *ai* is greatest. If the heights *ai* are equal, that one is most stable which has the greatest weight. Thus the modern automobile is built with as low a center of gravity as possible, to make its distance *ai* as great as possible, and floor lamps are weighted at the bottom to lower their center of gravity.

The condition of stable equilibrium for bodies which rest upon a horizontal plane is that a vertical line through the center of gravity shall fall within the base, the base being defined as the polygon formed by connecting the points at which the body touches the plane, as ABC (Fig. 80); for it is clear that in such a case a slight displacement must serve to raise the center of gravity along the arc of which OG is the radius. The larger the base of a body, the more stable its equilibrium, since it can be tipped through a greater angle before the vertical line through its center of gravity falls *outside* its base (Fig. 81). When this happens, the body must always fall; that is, its center of gravity must descend.

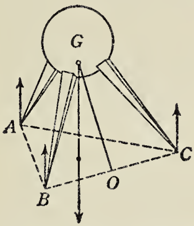


FIG. 80. Body in stable equilibrium

The condition of stable equilibrium for bodies supported from a single point, as in the case of a pendulum, is that the point of support shall be *above* the center of gravity. For example, the beam of a balance (Fig. 5, p. 13) cannot be in stable equilibrium, so that it will return to the horizontal position when slightly displaced, unless its center of gravity is below the knife-edge. (The pans are not to be considered, since they are not rigidly connected to the beam.)

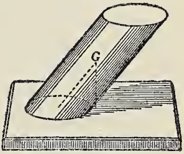


FIG. 81. Body not in equilibrium

Neutral and unstable equilibrium. A body is said to be in *neutral equilibrium* when, after a slight rotation, it tends neither to return to its original position nor to move farther from it. Examples of neutral equilibrium are a spherical ball lying on a smooth plane, a cone lying on its side, a wheel free to rotate about a fixed axis through its center, or any body supported at its center of gravity. In general, a *body is in neutral equilibrium when a slight rotation neither raises nor lowers its center of gravity.*

A body is in *unstable equilibrium* when, after a slight

tipping, it tends to move *farther* from its original position. A cone balanced on its point or an egg balanced on its end are examples. In general, *a body is in unstable equilibrium when a slight tipping lowers the center of gravity.* The motion then continues until the center of gravity is as low as possible. The condition for unstable equilibrium in the case of a body supported by a point is that the center of gravity shall be *above* the point of support.

Summary. Newton's law of universal gravitation. Any two bodies in the universe attract each other with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

The mass of a body is the quantity of matter, or material, in it. Its weight is the mutual attraction between it and the earth.

The mass of a body is constant everywhere; its weight varies with its geographical position.

The center of gravity of a body is the point of application of the resultant of all the downward forces of gravity acting upon the parts of the body, or the point at which the entire weight of the body may be considered as concentrated.

A body is in equilibrium when the resultant of all the forces acting upon it is zero.

A body is in stable equilibrium whenever slightly tipping it tends to raise the center of gravity.

A body is in neutral equilibrium when a slight rotation neither raises nor lowers its center of gravity.

A body is in unstable equilibrium when a slight tipping lowers the center of gravity.

QUESTIONS AND PROBLEMS

A

1. (*a*) Distinguish between mass and weight. (*b*) Could the fact that the weight of a body changes if it is taken from the equatorial to the polar region of the earth be shown by either a spring balance or a beam balance? Explain.

2. Do you get more sugar to the pound in Panama than in New York (*a*) when using a beam balance? (*b*) when using a spring balance? Explain.

3. What change would there be in your weight if your mass were to become four times as great and that of the earth three times as great, the radius of the earth remaining the same?

4. Upon what two factors does the weight of a body depend?

5. The pull of the earth on a body at its surface is 100 kg. Find the pull on the same body (*a*) 4000 mi above the surface; (*b*) 1000 mi above the surface; (*c*) 3 mi above the surface. (Take the earth's radius as 4000 mi.)

6. If a lead pencil is balanced on its point on the finger, it will be in unstable equilibrium; but if two knives are stuck into it, as in Fig. 82, it will be in stable equilibrium. Why?

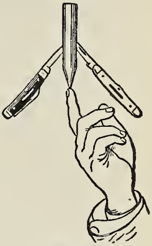


FIG. 82

B

1. What is the object of ballast in a ship?

2. What is (*a*) the most stable position of a brick? (*b*) the least stable position? Why?

3. In what state of equilibrium is a pendulum at rest? Why?

4. Why is a mucilage bottle made low and given a wide base?

5. In what two ways may a football guard increase his stability when playing in the line?

6. Give a reason why a load of hay is less stable than a load of brick.

7. Explain why the toy in Fig. 83 will not lie upon its side, but rises to the vertical position. Does the center of gravity rise?

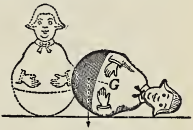


FIG. 83

8. Where is the center of gravity (*a*) of a hoop? (*b*) of a cubical box? (*c*) Is the latter more stable when empty or when full? Why?

9. (*a*) Where must the center of gravity of the beam of a balance be with reference to the supporting knife-edge *C*? (Fig. 5, p. 13.) Why? (*b*) Could you make a weighing if they coincided? Why?

Falling Bodies

Galileo's early experiments. Many of the familiar and important experiences of our lives have to do with falling bodies. Yet if we were asked the simple question Which

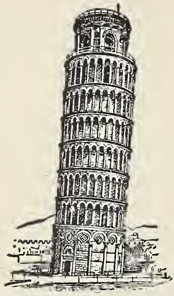


FIG. 84. Leaning tower of Pisa, from which were performed some of Galileo's famous experiments on falling bodies

would fall faster, a stone or a piece of lead? most of us would be uncertain of the answer. In fact, it was the asking and the answering of this very question by Galileo, about 1590, which may be considered as the starting point of modern physics.

We all know that light bodies like feathers fall slowly and that heavy bodies like stones fall rapidly, and up to Galileo's time it was taught in the schools that bodies fall with "velocities proportional to their weights." Not content with book knowledge, however, Galileo experimented with falling bodies himself. In the presence of the professors and students of the University of Pisa he dropped balls of different sizes and materials from the top of the tower of Pisa (Fig. 84), a distance of 180 feet, and found that they fell in almost the same time. He showed that even very light bodies, such as paper, fall with velocities which approach more and more nearly those of heavy bodies the more tightly they are wadded together. From these experiments he inferred that *all bodies, including the lightest, would fall at the same rate if it were not for the resistance of the air.*

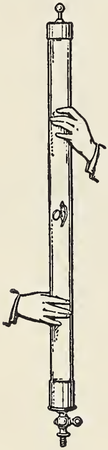
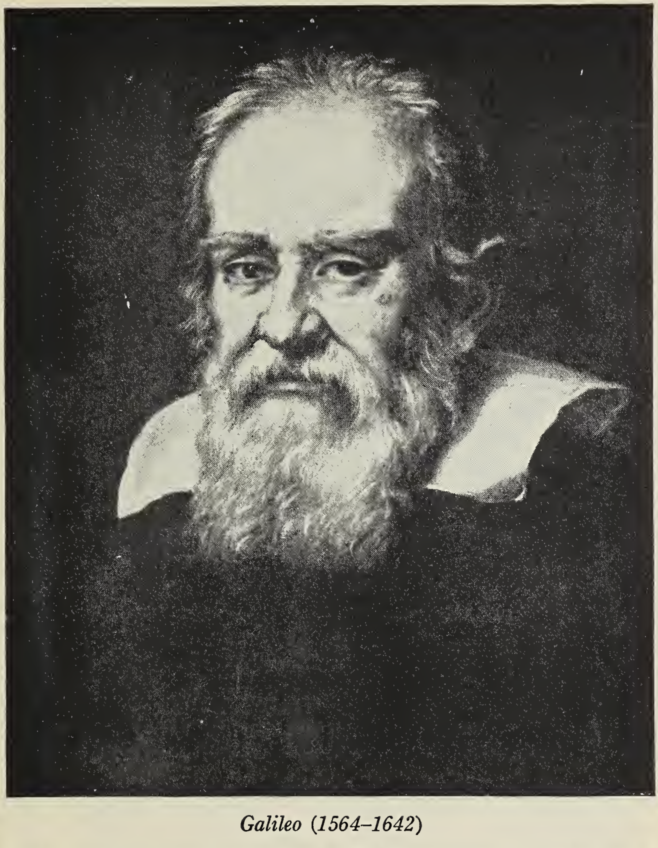


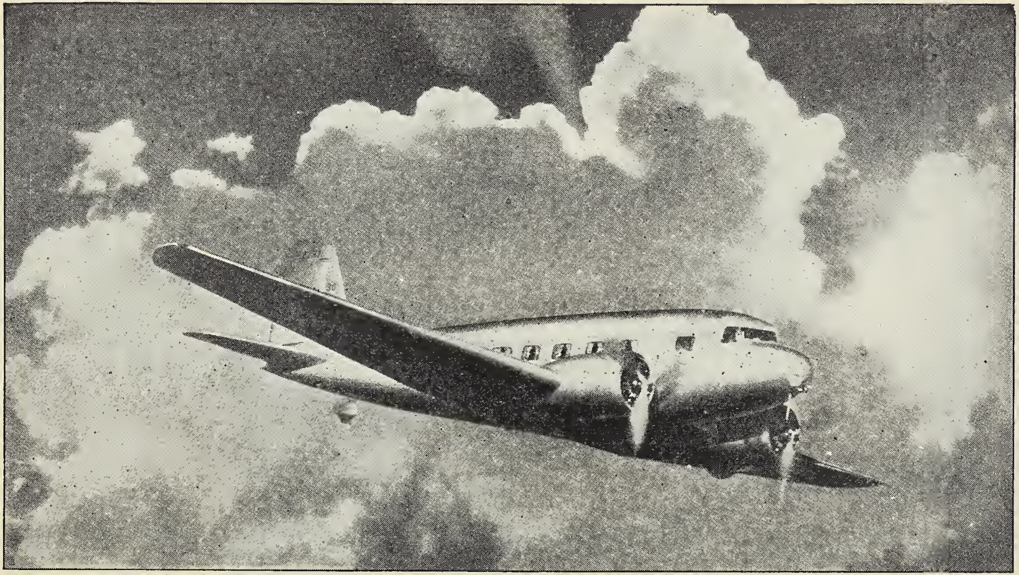
FIG. 85. Feather and coin fall together in a vacuum

The reason that feathers and other light objects fall more slowly can be shown by pumping the air out of a large glass tube containing a feather (or some small pieces of tissue paper) and a coin (Fig. 85). The more completely the air is taken out, the more nearly



Galileo (1564–1642)

Great Italian physicist, astronomer, and mathematician; "founder of experimental science"; son of an impoverished nobleman of Pisa; studied medicine in early youth, but forsook it for mathematics and science; was professor of mathematics at Pisa and at Padua; discovered the laws of falling bodies and the laws of the pendulum; was the creator of the science of dynamics; constructed the first thermometer; first used the telescope for astronomical observation; discovered Jupiter's satellites and the spots on the sun. Modern physics begins with Galileo



The Sky Chief

The Douglas fourteen-passenger air liner flying 210 miles per hour at 8000 feet. The *Sky Chief's* time for its regular flight from Los Angeles to New York is 15 hours

do the feather and the coin fall side by side when the tube is inverted. The air pump, however, was not invented until sixty years after Galileo's time.

Exact proof of Galileo's conclusion. To test Galileo's conclusion directly in the schoolroom is rather difficult because of the high speeds which falling bodies quickly attain. By allowing wood and steel balls to roll together down the inclined plane of Fig. 86, however, we can "dilute" the speeds, or slow them up, producing somewhat the same effect as that of a slow-motion picture. Instead of the whole weight

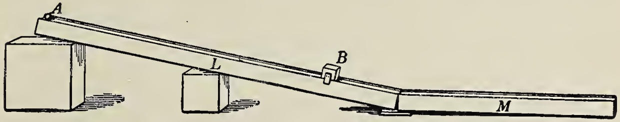


FIG. 86. Spaces traversed and velocities acquired by falling bodies in one, two, three, etc. seconds

of the balls acting on them to pull them to earth, we have but a small component of the force of gravity urging them down the plane. This small part is always exactly proportional to the entire weights of the two balls, and their "diluted" speeds will likewise be in proportion and more easily measured.

Start balls of steel and wood (preferably at least 1 in. in diameter) together down the inclined plane. They will be found to keep together all the way down. (If they roll in a narrow groove, they should have the same diameter; if on a wide track, the size is immaterial.) This experiment differs from that of the freely falling bodies only in that there is here practically no air resistance, because of the fact that the balls are moving more slowly.

In order to make them move still more slowly and at the same time to eliminate completely all possible effects due to the friction of the plane, Galileo suspended the different balls as the bobs of pendulums of exactly the same length and started them swinging through equal arcs, thus performing the first experiment on page 94. Since the bobs, as they pass

through any given position, are merely moving very slowly down the same inclined planes (Fig. 72), it is clear that they are in reality falling bodies slowed up in their action. Galileo thus found, as we did, that the times of fall — that is, the *periods* — of the pendulums are exactly the same.

From the preceding experiment we conclude with Galileo and with Newton (who performed it with the utmost care a hundred years later) that *in a vacuum the velocity acquired per second by a freely falling body is exactly the same for all bodies, regardless of their size or material.*

Relation between distance and time of fall. Will a body fall twice as far in 2 seconds as it does in 1? Our previous experience has probably taught us that bodies increase in speed as they fall, and so our probable answer to the preceding question would be No. Exactly what is the relationship between distance and time of fall? Since a freely falling body falls so rapidly as to make direct measurements upon it difficult, we will adopt Galileo's plan of studying the laws of falling bodies by observing the motion of a ball rolling down an inclined plane. The motion in this case is caused by the component of gravity parallel to the plane.

Support a grooved board 17 or 18 ft long as in Fig. 86, one end being about a foot above the other. Divide the side of the board into feet, and set the block *B* just 16 ft from the starting point of the steel ball *A*. Start a metronome or a clock beating seconds, and release the ball at the instant of one click of the metronome. If the ball does not hit the block so that the click produced by the impact of the ball coincides exactly with the fifth click of the metronome, alter the inclination until this is the case (this adjustment may well be made by the teacher before class). Now start the ball again at any click of the metronome, and note that it crosses the 1-foot mark exactly at the end of the first second, the 4-foot mark at the end of the second second, the 9-foot mark at the end of the third second, and hits *B* at the 16-foot mark at the end of the fourth second (Fig. 87). This can be tested more accurately by placing *B* successively at the 9-foot, the 4-foot, and the 1-foot mark and noting that the click produced by the impact coincides exactly with the proper click of the metronome.

Since 1, 4, 9, and 16 are the respective squares of the times 1, 2, 3, and 4 seconds, we conclude, with Galileo, that *the whole distance traveled by a falling body in any number of*

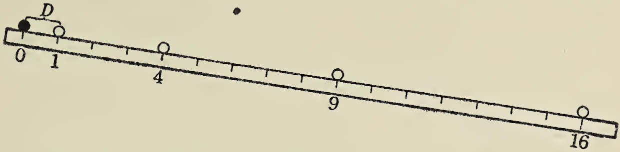


FIG. 87. Total distances traversed during four successive seconds

seconds is equal to the distance traveled during the first second times the square of the number of seconds; that is, if D represents the distance traveled during the first second, S the total space, and t the number of seconds, then $S = Dt^2$.

Relation between velocity and time of fall. In the last section we investigated the distances traveled in 1 second, 2 seconds, 3 seconds, and so on. Let us now study the *velocities* gained on the same inclined plane in 1 second, 2 seconds, 3 seconds, and so on.

Place a second grooved board M at the bottom of the incline, in the manner shown in Fig. 86. To neutralize friction the board should be given a slight slant, just enough to cause the ball to roll

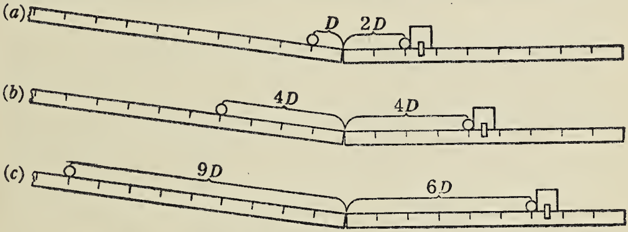


FIG. 88. Velocity at the close of successive seconds

along it with uniform velocity. Start the ball at a distance D (Fig. 88 (*a*)) up the incline, D being the distance which in the last experiment it was found to roll during the first second. It will

then just reach the bottom of the incline at the instant of the second click. Here it will be freed from the influence of gravity and will therefore move along the lower board with the velocity which it had at the end of the first second. It will be found that when the block is placed at a distance exactly equal to 2 D from the bottom of the incline, the ball will hit it at the exact instant of the third click of the metronome, that is, exactly 2 sec after starting; hence the velocity acquired in 1 sec is 2 D (Fig. 88 (a)). If the ball is started at a distance 4 D up the incline, it will take it 2 sec to reach the bottom, and it will roll a distance 4 D in the next second; that is, in 2 sec it acquires a velocity 4 D (Fig. 88 (b)). In 3 sec it will be found to acquire a velocity 6 D, etc. (Fig. 88 (c)).

The foregoing experiment shows that the precise meaning of the word *velocity* is *instantaneous rate* of motion, that is, the speed* at any instant. It is numerically equal to the distance through which the body will move per second provided that, at the instant considered, its rate of motion becomes uniform, as was the case in the experiment at the end of the first, second, and third seconds.

Acceleration. The experiment shows, secondly, that the gain in velocity of a falling body each second is the same; thirdly, that the amount of this gain is numerically equal to twice the distance traveled during the first second.

Motion in which velocity is gained or lost at a constant rate (as in the example given above) *is called uniformly accelerated motion.*

In uniformly accelerated motion the gain or loss each second in the velocity is called the acceleration. It is numerically equal to twice the distance traveled during the first second. An electric fan starting up from rest or slowing down when the current is turned off, a train leaving a station, and an automobile drawing away from the curb are all approximate examples of uniformly accelerated motion. Suppose the speed of the automobile at the end of the first second is 5 feet per second, at the end of the second second is 10 feet per

* For elementary purposes we will treat the two terms *velocity* and *speed* as having the same meaning. In more advanced work, however, *velocity* carries the additional idea of a particular direction.

second, at the end of the third second is 15 feet per second, etc. In this case there is a uniform gain of 5 feet per second in velocity every second. Notice that the time factor is given twice in order to name the unit completely. In writing or printing, in order to avoid this repetition an acceleration of 5 feet per second per second, for example, is often written or printed 5 ft/sec^2. One automobile is widely advertised to reach 25 miles per hour from a standing start in 8 seconds. This means that its acceleration is $\frac{25}{8} = 3.1$ miles per hour per second.

As brakes are applied to an automobile it loses velocity in a uniform manner if the braking force is kept constant. This loss in velocity per second is a negative acceleration, or *deceleration*, as was also the slowing down of the fan.

[**Formal statement of the laws of falling bodies.** Putting together the results of the last two sections, we obtain the following table, in which D represents the distance traveled during the first second in any uniformly accelerated motion.

Number of Seconds (t)	Velocity at the End of Each Second (v)	Gain in Velocity Each Second (a)	Total Distance Traveled (S)
1	$2\,D$	$2\,D$	$1\,D$
2	$4\,D$	$2\,D$	$4\,D$
3	$6\,D$	$2\,D$	$9\,D$
4	$8\,D$	$2\,D$	$16\,D$
...	...	...	...
t	$2t\,D$	$2\,D$	$t^2\,D$

Since D was shown on page 110 to be equal to half the acceleration a, we have at once, by substituting $\frac{1}{2}\,a$ for D in the last line of the table,

$$v = at; \quad (1)$$

$$S = \tfrac{1}{2}\,at^2. \quad (2)$$

[These formulas are simply the algebraic statement of the facts brought out by our experiments, but the reasons for these facts may be seen as follows:

[Since in uniformly accelerated motion the acceleration a is the velocity in centimeters or feet per second gained each

second, it follows at once that when a body starts from rest, that is, with an initial velocity of zero, its velocity at the end of t seconds is given by $v = at$. This is formula (1).

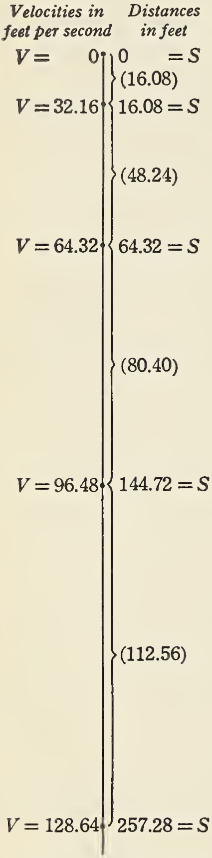


FIG. 89. A freely falling body

[To obtain formula (2) we have only to reflect that distance traveled is always equal to the average velocity multiplied by the time. When the initial velocity is zero, as in this case, and the final velocity is at, average velocity $= (0 + at) \div 2 = \frac{1}{2}\,at$. Hence

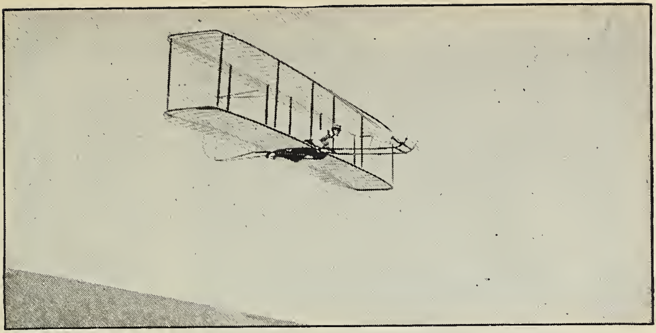
$$S = \tfrac{1}{2}\,at^2.$$

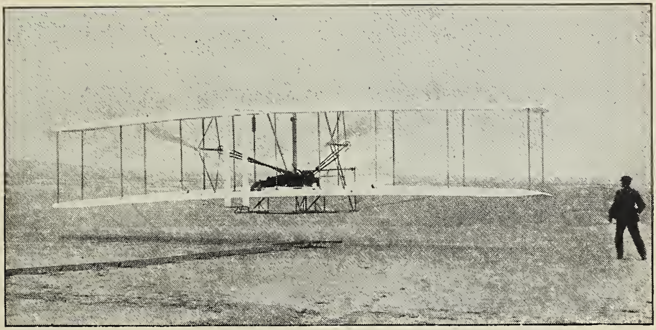
This is formula (2).

[These are the fundamental formulas of uniformly accelerated motion, but it is sometimes convenient to obtain the final velocity v directly from the total distance of fall S, or vice versa. This may be done, of course, by simply substituting in (2) the value of t obtained from (1); namely, v/a. This gives

$$v = \sqrt{2\,aS}. \qquad (3)$$

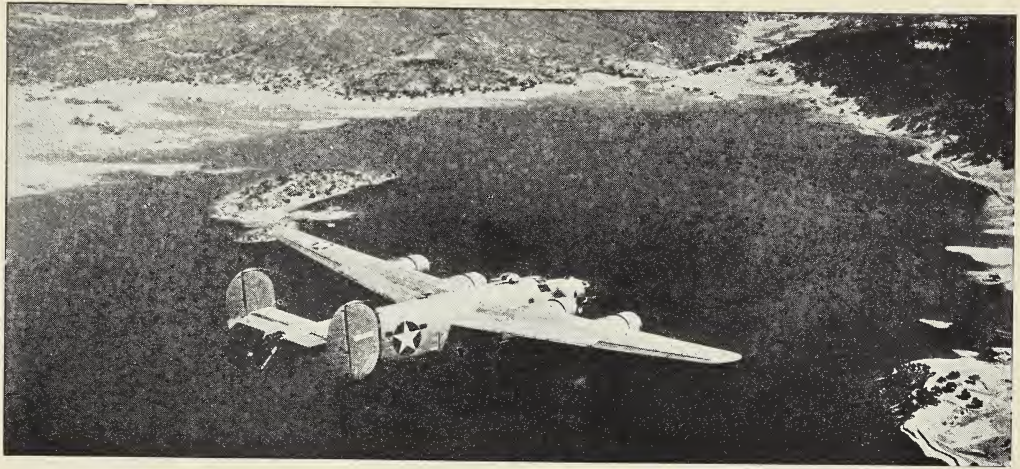
[**Acceleration of a freely falling body.** If in the experiment discussed on page 109 the slope of the plane is made steeper, the results will be precisely the same, except that the acceleration has a larger value. If the board is tilted until it becomes vertical, the body becomes a freely falling body (Fig. 89). In this case the distance traveled the first second is found to be 490 centimeters, or 16.08 feet. Hence the acceleration is 980 centimeters per second each second, or 32.16 feet per second each second. This acceleration of free fall, called the *acceleration of gravity*, is





The Wright Airplane

The most significant and far-reaching of the advances of the twentieth century — man's conquest of the air after centuries of failure — was made when the Wright brothers first introduced the principle upon which all successful flight by heavier-than-air machines now depends, namely, control of stability by the warping of wings, or by ailerons (hinged attachments to wings), in connection with the use of a rudder. The upper panel shows one of the original gliders (Wilbur Wright inside) with which the Wrights first mastered the art of gliding (1900–1903) and made more than a thousand gliding flights, some of them 600 feet long, following in this work the principles of gliding flight first demonstrated by Lilienthal and a little later, much more completely, by Chanute of Chicago (1895–1897). The lower panel shows "the first successful power flight in the history of the world" (Orville Wright in the machine, Wilbur running beside it as it rose from the track). Four such flights were made on the morning of December 17, 1903, the longest of which lasted 59 seconds and covered a distance of 852 feet against a 20-mile wind



Bombers — the Consolidated B-24

Long-range bombers, such as the above, must have a fuselage so shaped as to reduce as much as possible the resistance of the air. The Boeing Flying Fortress is another example of the heavy bomber. It weighs about 22 tons and carries a crew of nine to ten and a bomb load of about five tons. It has a range of 3500 miles and averages a speed of more than 300 miles per hour. Bombers liberate either high-explosive bombs or incendiary bombs. The high-explosive bombs range from fragmentation bombs weighing only 25 to 55 pounds up to demolition bombs weighing 600 to 12,000 pounds. The incendiary bomb is made of magnesium casings filled with thermit (a mixture of aluminum and iron oxide). (Courtesy of U. S. Army Air Forces)

usually denoted by the letter g. Notice that g does not stand for gravity, but for the *acceleration* due to the force of gravity. The numerical value of g varies slightly as measured at various points on the earth's surface, but the difference is never more than $\frac{1}{2}$ of 1 per cent.

For freely falling bodies, then, the three formulas of the preceding section become

$$v = gt, \tag{4}$$

$$S = \tfrac{1}{2} gt^2, \tag{5}$$

$$v = \sqrt{2\,gS}. \tag{6}$$

To illustrate the use of these formulas, suppose we wish to know with what velocity a body will hit the earth if it falls from a height of 200 meters, or 20,000 centimeters. From (6) we get

$$v = \sqrt{2 \times 980 \times 20{,}000}$$
$$= 6261 \text{ cm/sec.}$$

Effect of air resistance. It is understood that the preceding formulas apply strictly only to bodies falling freely in a vacuum. Comparatively light and bulky objects, such as paper and leaves, quickly reach such a speed that the resistance of the air acts as an equilibrant to the force of gravity. Heavier bodies take longer to do this, but even they finally reach a maximum speed. When the two forces are balanced, the bodies cease to be accelerated and fall with a *uniform* speed. Experiments seem to show that dummies, simulating human bodies in size and weight, reach a maximum speed of about 160 feet per second after they have fallen less than a third of a mile. (Calculate the theoretical value by means of formula (6) and compare the two answers.)

It is largely because of air resistance that the accurate determination of g is never made by direct measurement. The laws of the pendulum established on page 94 make this instrument by far the most accurate one obtainable for this determination. It is necessary only to measure the length l of a long pendulum and the time T between two successive passages of the bob across the mid-point, and then to substitute

in the formula $T = 2\pi\sqrt{l/g}$ in order to obtain g with a high degree of precision. The deduction of this formula is not suitable for an elementary text, but the formula itself may well be used for checking the value of g.

Height of ascent. If we wish to find the height S to which a body projected vertically upward will rise, we reflect that the time of ascent must be the initial velocity divided by the upward velocity which the body loses per second, that is, $t = v/g$; and the height reached must be this multiplied by the average velocity $\frac{v+0}{2}$, that is,

$$S = \frac{v^2}{2g}, \quad \text{or} \quad v = \sqrt{2gS}. \tag{7}$$

Since (7) is the same as (6), we learn that in a vacuum the speed with which a body must be projected upward to rise to a given height is the same as the speed which it acquires in falling from the same height.

Path of a projectile. Imagine a projectile to be shot along the line ab (Fig. 90). If it were not for gravity and the resistance of the air, the projectile would travel with uniform

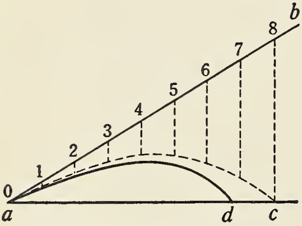


FIG. 90. The path of a projectile

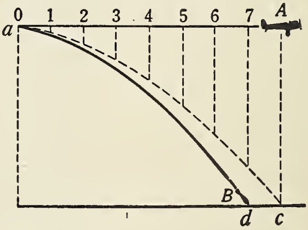


FIG. 91. The bomb B was released at a by the airplane A

velocity along the line ab, arriving at the points 1, 2, 3, etc. at the end of the successive seconds. Because of gravity, however, the projectile would be vertically below these points by the distances 16.08 feet, 64.32 feet, 144.72 feet, etc. Hence it would follow the path indicated by the dotted curve

(a parabola). But because of air resistance the height of flight and the range are diminished, and the general shape of the trajectory* is similar to the continuous curved line. Fig. 91 represents bomb-dropping by an airplane.

The airplane. The simplest way to illustrate the problem of flying is with a boy's kite. Suppose AB (Fig. 92 (*a*)) is a kite flying in a wind and held by a string; let us suppose also that the kite has no weight, and flies steadily in such a position that its surface makes the angle with the wind denoted by i. Now it is well known that the effect of the wind is twofold. It tends to raise the kite and to drive it back. These effects may be represented by the vertical line marked "*Lift*"

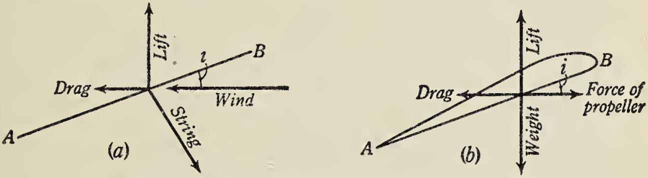


FIG. 92. Forces acting upon a kite and an airplane

and the horizontal line marked "*Drag.*" But since the string prevents the wind from doing what it tends to do, the tension in the string must just balance these two forces lift and drag. We explain this action by saying that the force in the string must be equal to the resultant of lift and drag, opposite in direction and applied at the same point. This resultant is found experimentally to be always nearly perpendicular to AB.

If instead of using one force in a string we use two independent forces, one downward to offset lift and the other forward to offset drag, we shall obtain the same result. In the airplane (Fig. 92 (*b*)) this is just what we do. The downward force is the weight of the airplane, which *in the state of steady motion* is just equal and opposite to the lift force, and the forward force is due to the propeller turned by the motor

* The path described by a moving projectile.

and is equal and opposite to the drag. In brief, *an airplane is supported because the force of the propeller drags it forward and this causes a relative wind to strike the wing in such a way as to develop a lift force equal to the weight of the plane.*

[Gliding flight. When the engine stops, the airplane glides to the ground under the action of gravity. Fig. 93 shows the forces acting in such gliding flight in still air. The surface is moving downward and forward at some angle *i* to the flight path *op*. The relative wind, which in still air is opposite in direction to the path *op*, produces on the wing an effect that may be represented by some resultant force *oa*, which, as explained on page 115, is nearly perpendicular to the surface of the plane. This resultant force *oa* may be resolved as before into a drag *oc* in the direction of the relative wind and a lift *ob* perpendicular to it. In order to investigate the balance of forces we must now also resolve the force of gravity, or the weight, into components parallel and perpendicular to the relative wind. The lift *ob* just balances the weight component *oB*, and the drag is balanced by the component *oC*. Hence we see that the component of the weight in the direction of the path in gliding flight is exactly equivalent to the pull of the propeller in normal horizontal flight.

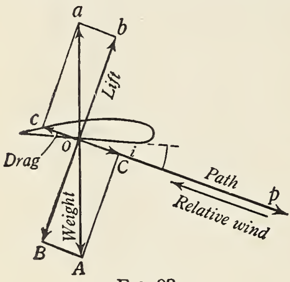
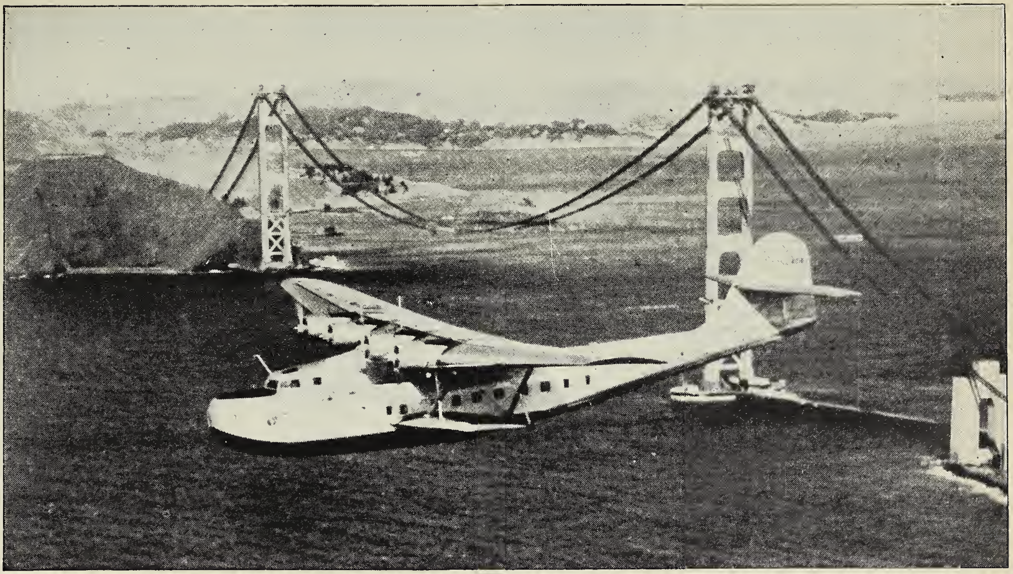


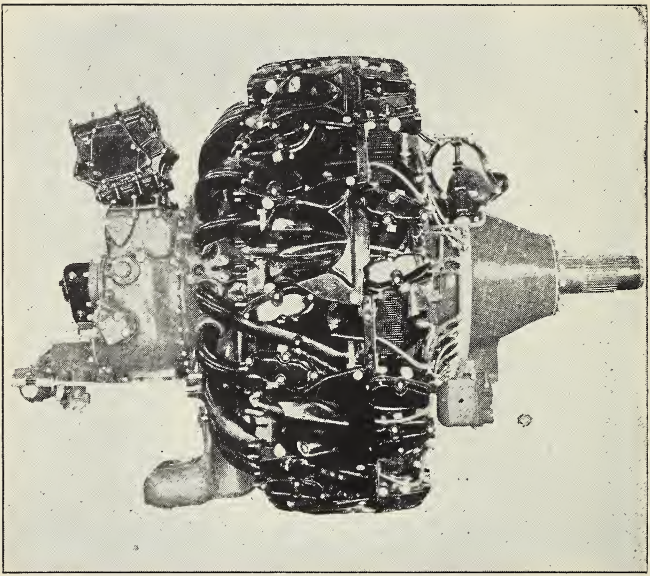
FIG. 93

[The origin of lift: Bernoulli's principle. It is quite obvious that, because of friction, we must experience a resistance, or drag, in pulling any body through a fluid, such as air or water. However, it is not quite so easy to see why we should also obtain in some cases a lift force perpendicular to the direction of motion. The complete and correct explanation of the phenomenon of airplane lift was given only at the beginning of this century and is based on the fundamental and important relation called Bernoulli's principle. A very simple



The China Clipper *Speeding West from the Golden Gate on the First Transpacific Flight for American Airways*

This huge flying boat has a wingspread of 130 feet and a gross weight of 51,000 pounds, develops 3200 horsepower with four engines, and has a cruising radius of 4000 miles. (Courtesy of the Glenn L. Martin Company, builders)



Airplane Engine

Compactness and a minimum weight per horsepower are prime requirements for the airplane engine. Such an engine weighs approximately one pound per horsepower. In addition, the fuel and oil consumption must be low. The modern airplane engine consumes about .45–.65 pounds of gasoline per horsepower-hour. The airplane engine must be adaptable to rapid changes in speed and resistant to vibration. The radial type of engine may have as many as 18 cylinders, arranged radially around a common crankshaft. (Courtesy of Wright Aeronautical Corporation)

experiment demonstrates the essential feature of this principle. Force water through a constricted pipe with pressure gauges at *a*, *b*, and *c* (Fig. 94). The pressure will be found to be lower at *b*, higher at *a* and *c*. Bernoulli's principle states that *there is in general such a relation between pressure and velocity*, and that *whenever the velocity of a fluid like air or water is high the pressure is low, and vice versa.*

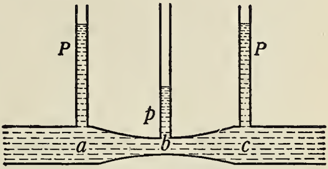


FIG. 94. Pressure is less at *b*, where speed is greater, than at *a* or *c*

Now the special shape of an airplane wing, with its curvature, smooth leading edge, and pointed trailing edge, has been developed because it makes the air travel faster over the top surface than over the bottom, as shown in Fig. 95, where the length of the arrows is proportional to the speed of the air. Then by Bernoulli's principle the pressure over the upper surface is low and that over the lower surface is high. The combination of the high pressure over the bottom and the suction over the top of the wing obviously gives a lift force tending to move the wing up. It was only when this lift-producing mechanism was clearly understood early in this century that it became possible, through an understanding of the characteristics necessary for efficient airplane wings, to design really efficient wing surfaces like those shown in Figs. 93 and 95.

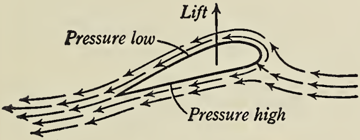


FIG. 95. The lift on an airplane

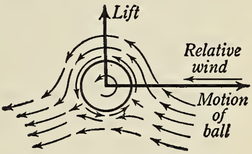


FIG. 96. A baseball curve

The curved ball. Another very striking illustration of Bernoulli's principle is furnished by the curved flight of a baseball when it is thrown with a spinning motion. In Fig. 96

the relative wind is from right to left, and the ball is spinning from right over left, as indicated by the arrows on the ball. Since the spinning of the ball carries air around with it, it is clear that this circulatory motion increases the wind velocity above the ball and decreases that below the ball, as is shown by the arrows. Then, applying Bernoulli's principle, we see that the pressure will be high below and low above the ball, giving a force which causes it to curve in the direction of its spin.

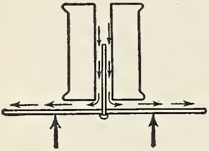


FIG. 97. Cardboard and spool

[The following experiment furnishes an additional striking illustration of Bernoulli's principle. Thrust a pin through a cardboard disk 3 in. in diameter (Fig. 97). Then thrust the pin into the hole of a spool and try to blow the cardboard off by blowing in at the other end. If the stream of air once gets started out between the cardboard and the spool, the harder you blow the harder does the higher pressure of the air outside push the cardboard back against the spool. As soon, however, as you cease trying to blow the cardboard off, it falls.

Summary. In a vacuum falling bodies descend at the same rate, regardless of their mass or size.

The total distance traversed by a falling body in any number of seconds is the distance traversed the first second times the square of the number of seconds, or $S = Dt^2$.

Velocity is the instantaneous rate of motion. It is numerically equal to the distance through which the body will move per second provided that, at the instant considered, its rate of motion becomes uniform. Acceleration is rate of change of velocity.

Uniformly accelerated motion is motion in which velocity is gained or lost at a constant rate. The acceleration is numerically equal to twice the distance traveled during the first second, or $a = 2\,D$. The velocity gained or lost equals the acceleration times the time, or $v = at$.

If the body starts from rest, its final velocity v and the distance S are related by $v = \sqrt{2\,aS}$.

For freely falling and freely rising bodies the acceleration is designated by g (= 980 centimeters per second each second = 32.16 feet per second each second).

The total distance traveled always equals AVERAGE VELOCITY times the TIME.

Any projectile falls away from its original path in accordance with the laws of freely falling bodies.

Bernoulli's principle states that in fluid motion wherever the velocity of flow is high the pressure is low. It is used to explain the lift of an airplane and the curved flight of a spinning ball.

QUESTIONS AND PROBLEMS

[For values of g it will be sufficiently accurate to use 32 ft/sec^2, or 980 cm/sec^2.]

A

1. Does the same force which causes objects to fall also cause balloons to rise? Explain.

2. One boy says a whole brick will fall twice as fast as half a brick because the earth pulls twice as much upon it; a second boy says it will fall half as fast because it is twice as hard to set in motion. What is the truth? Give reasons. Try it.

3. (*a*) A boat slid down a shoot-the-chutes, traveling 4 ft the first second. Without the use of formulas *tell* the answers to the following: (1) How far did the boat slide in 2 sec? 3 sec? 4 sec? 5 sec? (2) How far did it go during the fifth second? (3) What was the acceleration in ft/sec^2 (feet per second each second)? (4) What was the velocity at the close of the fifth second? (5) What was the average velocity during the first five seconds? (*b*) Using this average velocity, find how far the boat slid in 5 sec. Does this answer agree with your answer to the last part of (1)? (*c*) Using the velocities at the beginning and at the end of the fifth second, find the average velocity during the fifth second. Knowing this average, state the distance traveled during the fifth second. Does this agree with your answer to (2)?

4. An automobile starting from rest acquired a velocity of 10 mi/hr (miles per hour) in 5 sec. Assume that the acceleration was uniform; what was it (*a*) in mi/hr/sec (miles per hour per second)? (*b*) in mi/min/sec? (*c*) in ft/min/sec? (*d*) in ft/sec/sec?

5. A ball thrown across the ice started with a velocity of 80 ft/sec. It was retarded by friction at the rate of 2 ft/sec^2. (*a*) For how many seconds did it roll? (*b*) What was its average

velocity during this time? (*c*) On the basis of average velocity, how far did it go? (*d*) By the use of $S = \frac{1}{2}at^2$, find how far it went.

6. A skater on reaching a speed of 60 ft/sec began gliding and came to rest after traveling 600 ft. Find (*a*) his average velocity during the glide; (*b*) the time required to travel the 600 ft; (*c*) the acceleration.

B

1. A bullet was fired with a velocity of 2400 ft/sec from a rifle having a barrel 2 ft long. Find (*a*) the average velocity of the bullet while moving the length of the barrel; (*b*) the time required to move through the barrel; (*c*) the acceleration of the bullet while in the barrel.

2. A boy dropped a stone from a bridge and noticed that it struck the water in just 3 sec. (*a*) How fast was it going when it struck? (*b*) What was its average velocity during the 3 sec? (*c*) With this average velocity, how far must it have fallen in the 3 sec?

3. (*a*) (1) How much additional velocity will the pull of the earth impart each second to a freely falling body? (2) What velocity will it take away each second from a freely rising body? (*b*) A bullet is fired vertically upward with a velocity of 2400 ft/sec. Assuming no air resistance, find (1) how long it will take the pull of the earth to bring the bullet to rest; (2) the average velocity during the ascent; (3) the height to which the bullet rises, using average velocity and time of ascent; (4) the height of ascent, using $S = \frac{1}{2}gt^2$.

4. How far will a body fall from rest during the first half-second?

5. A baseball was thrown vertically into the air with a velocity of 160 ft/sec. How many seconds did it remain in the air?

6. A baseball was thrown upward. It remained in the air for 6 sec. (*a*) With what velocity did it leave the hand? (*b*) How high did it go?

7. (*a*) With what velocity must a ball be shot upward to rise to the height of the Washington Monument (555 ft)? (*b*) How long before it will return?

8. A ball was batted horizontally with a velocity of 100 ft/sec from the top of a tower 144 ft high. Plot its path on the way to the ground, assuming no air resistance.

9. A body starting from rest and moving with uniformly accelerated motion acquired a velocity of 60 ft/sec in 5 sec. Find (*a*) the

acceleration; (*b*) the average velocity during the 5 sec; (*c*) the total distance traveled in 5 sec.

10. How long will it take a trolley car starting from rest with an acceleration of 2.5 ft/sec^2 to travel 100 ft?

11. A ball shot straight upward near a pond was seen to strike the water in 10 sec. (*a*) How high did it rise? (*b*) What was its initial speed?

12. What forces support an airplane in flight?

13. A boy coasting downhill on a sled reaches level ground with a speed of 30 ft/sec. How far will he coast if friction decreases his speed at the rate of 2 ft/sec each second?

Newton's Laws of Motion

First law: inertia. If the brakes of an automobile are applied too suddenly, the passengers are thrown forward; if the automobile is started too suddenly from rest by throwing in the clutch too quickly, they are thrown back against the cushions. All our previous experiences support the assertion that bodies in motion tend to remain moving, and that bodies at rest resist sudden efforts to start them.

Again, a block will go farther when hit along an icy surface than along an asphalt pavement. Of course there is more friction between the block and the asphalt than between the block and the ice.

If there were no friction at all, when would a body stop? Astronomical observations furnish the most convincing answer to this question, for we cannot detect any retardation at all in the motions of the planets as they swing round the sun through empty space.

Furthermore, since mud flies off at a tangent from a rotating automobile wheel, or water from a whirling grindstone, and since, too, we have to lean inward to prevent ourselves from falling outward in going round a curve, it appears that bodies in motion tend to maintain not only the *amount* of their motion but also the *direction*. (See gyrocompass opposite page 215.)

To explain observations of this sort Sir Isaac Newton in 1686 made the following statement and called it the first law of motion:

Every body continues in its state of rest or of uniform motion in a straight line unless it is compelled by external force to change that state.

This property, which all matter possesses, of resisting any attempt to start it if at rest, to stop it if in motion, or in any way to change either the direction or the amount of its motion, is called *inertia.* The amount of inertia which a body has is found by experiment to be strictly proportional to its mass as measured with a beam balance, so that mass may be taken as the quantitative measure of inertia.

Centrifugal and centripetal force. Because of its inertia an automobile turning a corner at high speed tends to continue in a straight line and hence to skid when the pavement is wet. It is inertia alone which prevents the planets from falling into the sun, which causes a rotating sling to pull hard on the hand until the stone is released, and which causes the stone to fly off at a tangent to the circle around which it was being whirled. It is inertia which makes rotating liquids move out as far as possible from the axis of rotation (Fig. 98), which sometimes makes flywheels burst, which makes the equatorial diameter of the earth greater than the polar diameter, which makes the heavier milk move out farther than the lighter cream in the dairy separator, etc. Formerly the dairy farmer who wished to separate his more valuable cream from the milk placed the milk in broad shallow pans and allowed it to stand for 24 hours. The lighter cream gradually rose to the surface and was then skimmed off. The cream-separator accomplishes this separation more completely and in a few moments of time. (See opposite page 125.)

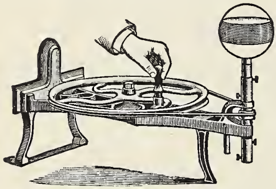
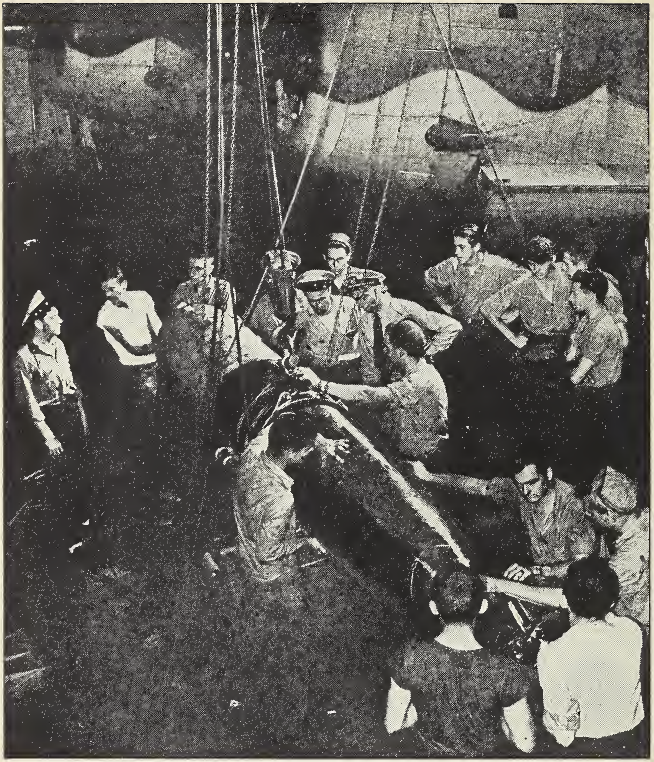


FIG. 98. Illustrating centrifugal force

Antiaircraft Gun

In addition to the former field artillery, the present war has introduced the antiaircraft gun. This is mounted on wheels or on a fixed platform. It is a rapid-firing gun, adapted to the rapid adjustment of sights and a quick change in the angle of elevation. The antiaircraft gun fires projectiles of one to thirty-three pounds and has a vertical range of as much as 30,000 feet. (Courtesy of U. S. Army Signal Corps)



Torpedoes

Torpedoes are fired from tubes of a submarine or warship, or they may be liberated from airplanes. The submarine torpedo represents one of the most elaborate instruments of warfare. By means of a mechanism which operates horizontal rudders it can be set for a definite depth. By means of a gyroscope which operates vertical rudders it can be held to a definite direction. Such a torpedo weighs about one and one-half tons and has a range of about 30,000 feet. It is propelled by a reciprocating engine or gas turbines within the torpedo. It is operated by compressed air mixed with fuel such as alcohol or kerosene. The head of the torpedo usually contains a 500-pound explosive charge of T.N.T. (Courtesy of U. S. Navy)

Inertia manifesting itself in this tendency of the parts of rotating systems to get farther from the center of rotation is called centrifugal ("center-fleeing") *force.*

In *all* rotating systems this tendency of the parts to get farther from the center is counteracted by a force acting toward the center. The gravitational attraction of the sun, for example, is the force which keeps the earth from flying off tangentially into space. *This inward, centrally acting force which comes into play in all rotating systems is called centripetal* ("center-seeking") *force.*

Other applications of centrifugal force. Commercial laundries remove most of the water in the washed clothes by whirling them at high speeds in a large cylinder perforated with many holes. Some types of electric washing machines for the home use this same principle instead of the usual wringer.

In the process of making sugar the crystals which form in the mother liquor are partly dried by a similar device, called a centrifuge. The centrifuge is widely used to remove sediment from liquids, to remove the precipitate from the filtrate in chemistry, and to test milk and cream for their percentage of butterfat. The centrifugal principle is used in centrifugal water pumps (Fig. 99), now extensively employed in lifting large quantities of water to considerable heights. Such pumps are also used in dredging and other operations where much sediment would clog the valves of the ordinary water pump. The water enters the rotor horizontally at the center and, after passing through the carefully shaped streamlined vanes, emerges with an upward-directed momentum which in the new Los Angeles aqueduct lifts the water to a height as great as 700 feet. Such pumps reach an efficiency as high as 90 per cent. (See opposite page 34.)

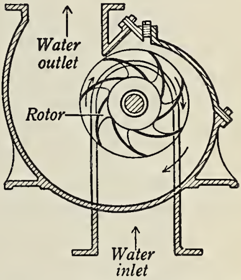


FIG. 99. Vertical section of a centrifugal pump

Fig. 205, p. 264, shows how the centrifugal governor on a steam engine operates to keep its speed uniform.

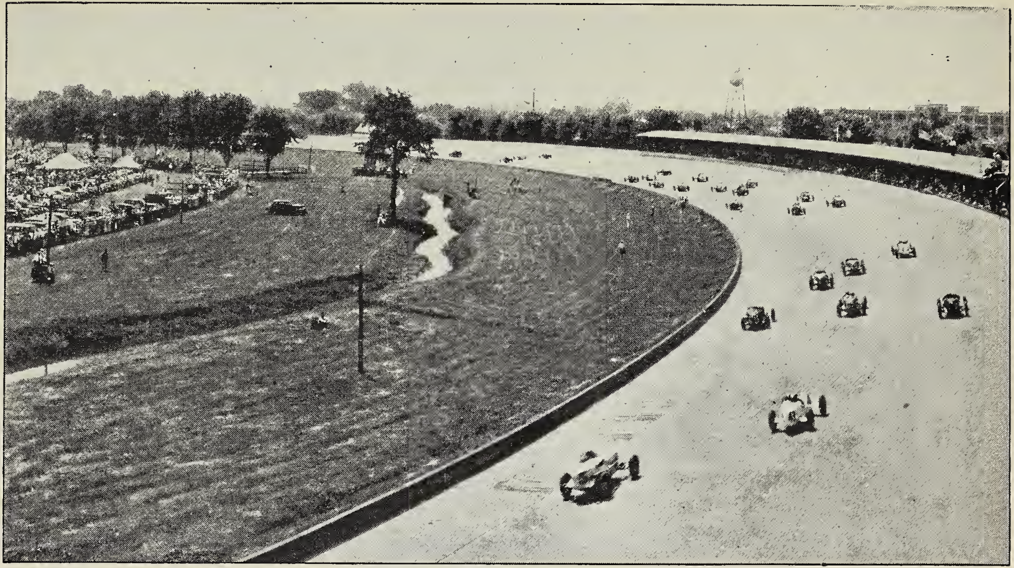
Measurement of centrifugal force. If one whirls a weight around in a circle by means of an attached string, he finds that he must exert a force inward (centripetal force) to neutralize the centrifugal force urging the weight to fly off at a tangent. If he uses a larger weight, this force will be greater; if he whirls the weight faster, the force will likewise be greater; but if he uses a longer string (keeping the speed the same), he finds that the force is less. Evidently centrifugal force depends on three factors: mass, velocity, and radius of rotation. The exact formula to show this relationship is

$$F = \frac{mv^2}{r}. \qquad (8)$$

If m is the mass in grams, v the velocity in centimeters per second, and r the radius in centimeters of the circle of rotation, then the force F will be expressed in dynes (p. 125).

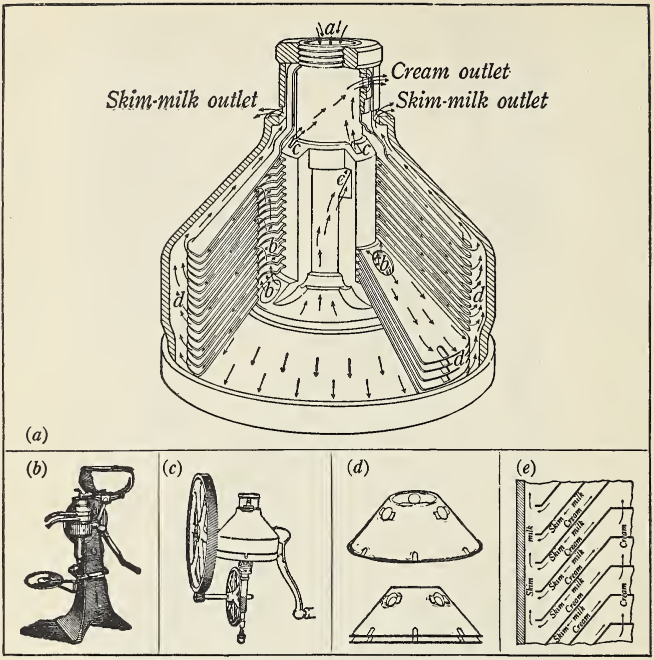
Momentum. An ocean liner moving at a very slow speed may cause great damage to the pier which it strikes; winds may blow tiny particles of sand at high velocities, so that the sand will wear away great rocks. The effect produced evidently depends not only on the mass of the body but also on its rate of motion. The quantity of motion possessed by a moving body is defined as the product of the mass and the velocity of the body. It is commonly called *momentum.* Thus, a 10-gram bullet moving 50,000 centimeters per second has 500,000 units of momentum; a 1000-kilogram pile-driver moving 1000 centimeters per second has 1,000,000,000 units of momentum; etc. We will always express momentum in C.G.S. units; that is, as a product of grams by centimeters per second.

Second law. Newton's first law stated that objects tend to remain at rest, or if in motion to continue in a straight line at the same speed, unless acted on by some outside force. The second law tells what happens when this outside force is applied so as to change this condition of rest or motion.



Outwitting Centrifugal Force

The motor speedway is highly banked on the turns so as to hold the machines on the track against the centrifugal forces called into play by the enormous speeds involved



The Cream-separator

The milk is poured into a central tube (see (*a*) *a*) at the top of a nest of disks (see (*a*) and (*d*)) situated within a steel bowl. The milk passes to the bottom of the central tube, then rises through three series of holes (see (*a*) *b*, *b*, *b*, etc.) in the nest of disks, and spreads outward into thin sheets between the slightly separated disks. By means of a system of gears (see (*c*)) the disks and bowl are made to revolve from 6000 to 8000 revolutions per minute. The separation of cream from skim milk is quickly effected in these thin sheets; the heavier skim milk (water, casein, and sugar) is thrown outward by centrifugal force against the undersurfaces of the bowl disks (see (*e*)), then passes downward and outward along these undersurfaces to the periphery of the bowl (see (*a*) *d*, *d*, *d*, etc.), and finally rises to the skim-milk outlet. The lighter cream is thereby at the same time displaced inward and upward along the upper surfaces of the bowl disks (see (*e*)), then passes over the inner edges of the disks to slots (see (*a*) *c*, *c*, *c*, etc.) on the outside of the central tube, and finally rises to the cream outlet, which is above the outlet for the skim milk (see (*a*) and (*b*)). It may be adjusted to vary the amount of cream removed

Since a 2-gram mass is pulled toward the earth with twice as much force as is a 1-gram mass, and since both, when allowed to fall, acquire the same velocity in a second, it follows that in this case *the momentums produced in the two bodies by the two forces are exactly proportional to the forces themselves.* In all cases in which forces simply overcome inertia this rule is found to hold. Thus a 3000-pound pull on an automobile on a level road, where friction may be neglected, imparts in a second just twice as much velocity, and hence twice as much momentum, as a 1500-pound pull does. In view of this relation Newton's second law of motion was stated thus: *Rate of change of momentum is proportional to the force acting, and the change takes place in the direction in which the force acts.*

The dyne. Since the gram of force varies somewhat with locality, it has been found convenient for scientific purposes to devise another unit of force which would be independent of geographical position. Newton's second law is taken as a basis for its definition. It is called an absolute, or C.G.S., unit because it is based upon the fundamental units of length, mass, and time, and is therefore independent of gravity. It is named the *dyne* and is defined as *the force which, acting for 1 second upon any mass, imparts to it 1 unit of momentum*; or *the force which, acting for 1 second upon a 1-gram mass, produces a change in its velocity of 1 centimeter per second.*

A gram of force equivalent to 980 dynes. A gram of force was defined as the pull of the earth upon 1 gram of mass. Since this pull is capable of imparting to this mass in 1 second a velocity of 980 centimeters per second (that is, 980 units of momentum), and since a dyne is the force required to impart in 1 second 1 unit of momentum, it is clear that the gram of force is equivalent to 980 dynes of force. The dyne is therefore a very small unit, about equal to the force with which the earth attracts a cubic millimeter of water or to the force exerted by a postage stamp lying on the hand.

[**Algebraic statement of the second law.** Let mv be the total momentum gained in t seconds when a force of F grams acts

on a body. Then the momentum gained in *one* second will be $\frac{mv}{t}$. Since the force in dynes is equal to the momentum imparted per second, we have

$$F = \frac{mv}{t}, \text{ or } Ft = mv. \tag{9}$$

In other words, momentum is proportional to the product of the force acting by the time during which it acts. Now

$$\frac{v}{t} = a. \tag{10}$$

Substituting in equation (9) we have

$$F = ma. \tag{11}$$

This is merely stating in the form of an equation that force is measured by the rate of change of momentum.

The third law. When a man jumps from a boat to the shore, we all know that the boat is pushed backward; when a bullet is shot from a gun, the gun recoils, or "kicks"; when one billiard ball hits another, it loses speed, that is, it is pushed back while the second ball is pushed forward. The following simple experiment will illustrate how effects of this sort may be studied quantitatively:

Let a steel ball A (Fig. 100) fall from a position C against another exactly similar ball B. In the impact A will lose practically all its velocity, and B will move to a position D, which is at the same height as C. Hence the velocity acquired by B is almost exactly equal to that which A had before the impact. These velocities would be exactly equal if the balls were perfectly elastic. It is found to be true experimentally that the momentum acquired by B plus that retained by A is exactly equal to the momentum which A had before the impact. The momentum acquired by B is therefore exactly equal to that lost by A. Since, by the second law, change in momentum is proportional to the force acting, this experiment shows that *A pushed forward on B with precisely the same force with which B pushed back on A.*

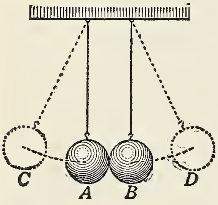


FIG. 100. Illustration of third law

Now the essence of Newton's third law is the assertion that in the case of the man jumping from the boat the mass of the man times his velocity is equal to the mass of the boat times its velocity, and that in the case of the bullet and the gun the mass of the bullet times its velocity is equal to the mass of the gun times its velocity. The truth of this assertion has been established by a great variety of experiments.

Newton stated his third law thus: *To every action there is an equal and opposite reaction.*

Since force is measured by the rate at which momentum changes, this is only another way of saying that *whenever a body acquires momentum, some other body acquires an equal and opposite momentum.*

It is not always easy to see at first that setting one body into motion involves imparting an equal and opposite momentum to another body. For example, when a gun is held against the earth and a bullet is shot upward, we are conscious only of the motion of the bullet; the other body in this case is the earth, and its momentum is the same as that of the bullet. On account of the greatness of the earth's mass, however, its velocity is negligible.

Striking examples of the law of reaction are the rotary lawn-sprinkler and the fireworks device known as a pin wheel.

Summary. Newton's three laws of motion. First law: Every body continues in its state of rest or of uniform motion in a straight line unless compelled by external force to change that state.

This tendency to resist any change is called inertia.

The inertia of rotating bodies, by virtue of which they tend to fly off at a tangent to the circle of rotation if the restraining force is released, is called centrifugal force.

Second law: Rate of change of momentum is proportional to the force acting, and the change takes place in the direction in which the force acts.

Third law: To every action there is an equal and opposite reaction.

Momentum $= mv =$ mass times velocity.

The absolute C.G.S. unit of force is that force which, acting for 1 second on a 1-gram mass, produces a change in its velocity of 1 cen-

timeter per second. This unit of force is called the dyne. In C.G.S. units Newton's second law of motion, expressed as a formula, becomes

$$F = \frac{mv}{t} = ma.$$

QUESTIONS AND PROBLEMS

A

1. How is inertia manifested when one steps off a moving trolley car while facing toward the rear?

2. How does inertia enter into the pitching, batting, and catching of a baseball?

3. Explain according to Newton's second law why an engine exerts a greater pull while giving speed to the train than after full speed is attained.

4. What principle is applied when one tightens the head of a hammer (*a*) by bringing the outer end of the handle down quickly on an anvil? (*b*) by holding the hammer at rest and sharply striking the outer end of the handle endwise with another hammer?

FIG. 101

5. If the trains *A*, *B*, and *C* (Fig. 101) are all running 60 mi/hr, what is the velocity of *A* with reference (*a*) to *B*? (*b*) to *C*?

6. Why does a flywheel cause machinery to run more steadily? (See opposite page 277.)

7. (*a*) Why does not the car *C* of Fig. 102 fall? (*b*) What carries it from *B* to *D*?

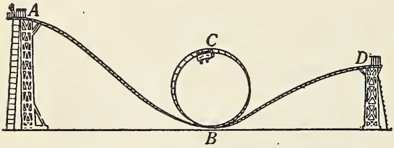


FIG. 102. A very ancient loop-the-loop

8. Balance a calling card on the finger and place a coin upon it. Snap out the card, leaving the coin balanced on the finger. What principle is illustrated?

9. Suspend a weight by a string. Attach a piece of the same string to the bottom of the weight. If the lower string is pulled with a sudden jerk, it breaks; but if the pull is steady, the upper string will break. Explain.

B

1. State where a body weighs the more: at the poles or at the equator. Give two reasons.

2. If a 10-gram bullet is shot from a 5-kilogram gun with a speed of 400 m/sec, what is the backward speed of the gun?

3. (*a*) If a team of horses pulls 500 lb in drawing a wagon, with what force does the wagon pull backward upon the team? (*b*) Why do the wheels turn before the hoofs of the horses slide?

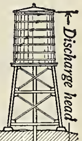
4. Why does a falling apple in striking your head exert a force in excess of its weight?

5. Why is a running track banked at the turns?

6. If the earth were to cease rotating on its axis, would bodies on the equator weigh more or less than they do now? Explain.

7. State how the third law is involved in rotary lawn-sprinklers.

8. Explain how reaction pushes the ocean liner and the airplane forward.



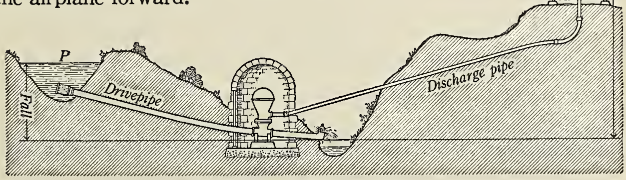


FIG. 103. Hydraulic ram

9. The hydraulic ram (Fig. 103) is a practical illustration of the principle of inertia. With its aid, water from a pond *P* can be raised into a tank that stands at a higher level than the pond. With the aid of Fig. 104 explain how it works, remembering that the valve *V* will not close until the stream of water flowing around it acquires sufficient speed. Why is there air in the upper part of the dome?

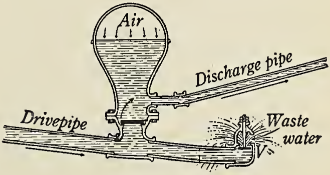


FIG. 104

10. If two men were together in the middle of a perfectly smooth (frictionless) pond of ice, how could they get off? Could one man get off if he were there alone?

11. From an analysis of the algebraic statement of Newton's second law explain why in catching a swift baseball your hands are stung less when you let them "give" to the impact of the ball than when they are held rigidly in place.

12. What change will there be in the inertia of a body as it is taken farther and farther from the surface of the earth?

13. If one ball is thrown horizontally from the top of a tower and another dropped at the same instant, which will strike the earth first? (Remember that the acceleration produced by a force is in the direction in which the force acts and proportional to it, whether the body is at rest or in motion. See second law, p. 124.) If possible, try the experiment with an arrangement like that of Fig. 105.

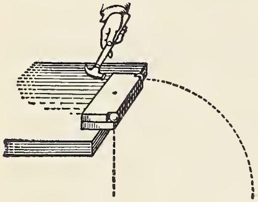


FIG. 105

14. A rifle weighing 5 lb discharges a 1-ounce bullet with a velocity of 1000 ft/sec. What will be the velocity of the rifle in the opposite direction? (Solve by Newton's third law.)

15. A pull of a dyne acts for 3 sec on a mass of 1 g. What velocity does it impart?

16. A force of 1 dyne acts on 1 g for 1 sec. How far has the gram been moved at the end of the second?

17. Which has the greater momentum, a 200-pound football back running 20 ft/sec or a 150-pound back running 25 ft/sec?

CHAPTER VI

Molecular Forces*

Molecular Forces in Solids; Elasticity

Tenacities. The molecules of solids are in motion at high speeds. Yet solids do not expand indefinitely like gases, neither do they evaporate like liquids. In fact, to pull their molecules apart often requires tremendous forces. Thus a rod of cast steel 1 centimeter in diameter can be loaded with a weight of 7.8 tons before it will be pulled in two. This property of solids is called *tenacity*.

The following are the weights in kilograms necessary to break drawn wires of different materials 1 square millimeter in cross section, the so-called relative tenacities of the wires.

Lead, 2.6	Platinum, 43	Iron, 77
Silver, 37	Copper, 51	Steel, 91

Elasticity. We can obtain additional information about the molecular forces existing in different substances by studying what happens when the weights applied are not large enough to break the wires.

Thus suspend a long steel wire (for example, No. 26 piano wire) from a hook in the ceiling and wrap the lower end tightly about one end of a meter stick, as in Fig. 106. Place a fulcrum *c* in a notch in the stick at a distance of about 5 cm from the point of attachment to the wire, and provide the other end of the stick with a knitting needle, one end of which is opposite the vertical mirror scale *S*. Apply enough weights to the pan *P* to place the wire under slight tension; then take the reading of the pointer *p* on the scale *S*.

* This chapter should be preceded by a laboratory experiment in which Hooke's law is investigated by the pupil for certain kinds of deformation easily measured in the laboratory. See, for example, Experiment 13 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

Add three or four kilogram weights successively to the pan and read the corresponding positions of the pointer. Now take the readings again as the weights are successively removed. In this last operation the pointer will probably be found to come back exactly to its first position.

The property which the steel has shown in this experiment, of returning to its original length when the stretching weights are removed, is possessed to a greater or less extent by all solid bodies. It is called *elasticity.* The greater the load required to produce a given stretch per centimeter of length, the more elastic the solid. This technical definition of elasticity is quite different from the popular conception. Most people think that rubber, because it will stretch a long distance, is highly elastic. When the standard above is applied, however, its elasticity is small compared with that of steel.

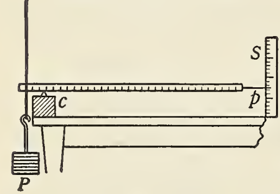


FIG. 106. Elasticity of a steel wire

Limits of perfect elasticity. If a sufficiently large weight is applied to the end of the wire of Fig. 106, it will be found that the pointer does not return exactly to its original position when the weight is removed. We say, therefore, that steel is *perfectly elastic* only so long as the distorting forces are kept within certain limits, and that as soon as these limits are overstepped it no longer shows perfect elasticity. Different substances differ very greatly in the amount of distortion which they can sustain before they fail to return completely to the original shape. When they do not so return, we say that the *elastic limit* has then been passed. The elastic limit of lead, for instance, is extremely small; hard-drawn brass and tempered steel, on the other hand, have an extremely high elastic limit in comparison. The architect or engineer, using these and other materials in his design and construction, must know

these limits accurately. Many of these data are available in engineering handbooks.

Hooke's law. If we examine the stretches produced by the successive addition of kilogram weights in the experiment of Fig. 106, we shall find that these stretches are all equal, at least within the limits of observational error. Very carefully conducted experiments have shown that this law, namely that the successive application of equal forces produces a succession of equal stretches, holds very exactly for all sorts of elastic displacements so long, and only so long, as the limits of perfect elasticity are not overstepped.

Besides changing the length of a body, forces may act in other ways to change its shape or size. The force of the automobile engine is transmitted to the rear wheels through the drive shaft. Here there is a twisting effect called *torsion.* Iron or wood beams in a floor bend slightly under the load on them; concrete pillars or columns withstand a crushing effect, in which the molecules tend to be pushed together. The column is then said to be under *compression.* It is an interesting fact that concrete withstands compression loads much better than tensional ones. When a load is placed on a concrete floor, the upper layers are in compression while the lower layers are in tension. To strengthen such a floor, light steel rods, which have great tensional strength (that is, great resistance to being pulled apart), are laid in the lower layers of the concrete. Such concrete is called reinforced concrete, and is used widely in construction work.

In all these cases Hooke's law, named after the Englishman Robert Hooke (1635–1703), holds within the elastic limits. It may be stated as follows: *Within the limits of perfect elasticity, elastic deformations of any sort, whether they are twists or bends or stretches, are directly proportional to the forces producing them*; more briefly, *the strain is directly proportional to the stress.* The common spring balance (Fig. 64) is an application of Hooke's law.

Cohesion and adhesion. The preceding experiments have brought out the fact that, in the solid condition at least,

molecules of the same kind exert attractive forces upon one another. That molecules of *unlike* substances also attract one another with forces which are at times very great is shown by the fact that glue sticks to wood, mortar to bricks, nickel to iron (as in nickel-plating), etc.

The forces which bind *like* kinds of molecules together are commonly called *cohesive forces*; those which bind together molecules of *unlike* kind are called *adhesive forces*. Thus we say that mucilage sticks to wood because of *adhesion*, and wood itself holds together because of *cohesion*. Again, adhesion holds the chalk to the blackboard; cohesion holds together the particles of the chalk.

Summary. Hooke's law. **Within the limits of perfect elasticity deformations are directly proportional to the forces producing them.**
Cohesion is the mutual attraction between molecules of *like* kind.
Adhesion is the mutual attraction between molecules of *unlike* kind.

QUESTIONS AND PROBLEMS

1. If a given weight is required to break a given wire, (*a*) how much force is required to break two such wires hanging side by side? (*b*) to break one wire of twice the diameter?

2. Why are springs made of steel rather than of copper?

3. If the position of the pointer on a spring balance is marked when no load is on the spring, and again when the spring is stretched with a load of 10 g, and if the space between the two marks is then divided into ten equal parts, will each of these parts represent a gram? Why?

4. A broken piece of wrought iron or steel may be welded by heating the broken ends white-hot and pounding them together. Gold foil is welded cold in the process of filling a tooth. Explain welding.

5. A piece of broken wood may be mended with glue. What does the glue do?

6. A damp cloth may absorb water more quickly than a dry one. Why?

7. A wire which is three times as thick as another of similar material will support how many times as much weight?

8. What must be the cross section of a wire of copper if it is to have the same tensile strength (that is, break with the same weight) as a wire of iron 1 mm^2 in cross section? (See page 131.)

9. Tell how you may, by the use of Hooke's law and a 20-pound weight, make the scale for a 32-pound spring balance.

Molecular Forces in Liquids; Capillary Phenomena

Proof of molecular forces in liquids. Since liquids change their shapes easily to conform to the shape of a containing vessel, we might suspect that there is little or no force of attraction between their molecules. A simple experiment will show that this is not true.

By means of sealing wax and string suspend a glass plate horizontally from one arm of a balance, as in Fig. 107. After equilibrium is obtained place a surface of water just beneath the plate and push the beam down until contact is made. It will be found necessary to add a considerable weight to the opposite pan to pull the plate away from the water. Since a layer of water will be found to cling to the glass, it shows that the added force was necessary to pull water molecules away from water molecules, not to pull glass away from water. Similar experiments may be performed with all liquids. In the case of mercury the glass will not be found to be wet, showing that the cohesion of mercury is *greater* than the adhesion of glass and mercury.

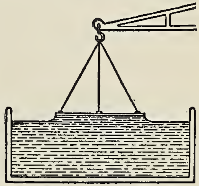


FIG. 107. Illustrating cohesion of water

Shape assumed by a free liquid. Since every molecule of a liquid is pulling on every other molecule, any body of liquid which is free to take its natural shape — that is, which is acted on only by its own cohesive forces — must draw itself together until it has the smallest possible surface for its volume; for since every molecule in the surface is drawn toward the interior by the attraction of the molecules within, it is clear that molecules must continually move toward the center of the mass until the whole has reached the most

compact form possible. Now the geometrical figure which has the smallest area for a given volume is a sphere. We conclude, therefore, that if we could free a body of liquid from the pull of gravity and other outside forces, it would at once take the form of a perfect sphere. This conclusion may be easily proved by the following experiment:

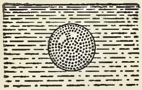


FIG. 108. A spherical globule of oil, freed from action of gravity

Pour alcohol upon the top of water in a wide *flat-sided* bottle. Then with a pipette insert a large globule of oil at the bottom of the layer of alcohol. The oil will be seen to float as a perfect sphere within the body of the liquid (Fig. 108).

Liquids do not commonly take the spherical form, because ordinarily the force of gravity is so large as to influence their shape much more than do their cohesive forces. To prove this statement we have only to observe that as a body of liquid becomes smaller and smaller,— that is, as the gravitational forces upon it become less and less,— it does indeed tend more and more to take the spherical form. Thus very small globules of mercury on a table will be found to be almost perfect spheres, and small raindrops or minute *floating* particles of all liquids are very nearly spherical.

Contractility of liquid films; surface tension. The tendency of liquids to assume the smallest possible surface furnishes a simple explanation of the contractility of liquid films.

Blow a soap bubble 2 or 3 in. in diameter on the bowl of a pipe and then watch it. It will at once begin to shrink in size, and in a few minutes will disappear within the bowl of the pipe. The liquid of the bubble is simply obeying the tendency to reduce its surface to a minimum, a tendency arising entirely from the mutual attractions which its molecules exert upon one another. A candle flame held opposite the opening in the stem of the pipe will be deflected by the current of air which the contracting bubble is forcing out through the stem.

Again, tie a loop of fine thread to a wire ring, as in Fig. 109. Dip the ring into a soap solution so as to form a film across it, and then thrust a hot wire through the film inside the loop. The tendency

of the film outside the loop to contract will instantly snap out the thread into a perfect circle (Fig. 110). The reason that the thread takes the circular form is that, since the film outside the loop is

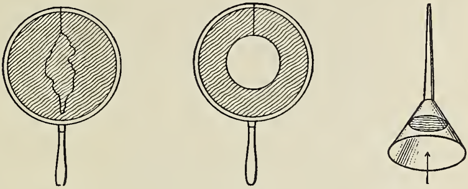


Fig. 109 Fig. 110 Fig. 111

Illustrating the contractility of soap films

trying to assume the smallest possible surface, the area inside the loop must of course become as large as possible. The circle is the figure which has the largest possible area for a given perimeter.

Form a soap film across the mouth of a clean 2-inch funnel, as in Fig. 111. The tendency of the film to contract will be sufficient to lift its weight against the force of gravity.

The tendency of a liquid to reduce its exposed surface to a minimum, that is, *the tendency of any liquid surface to act like a stretched elastic skin or membrane*, is called *surface tension.*

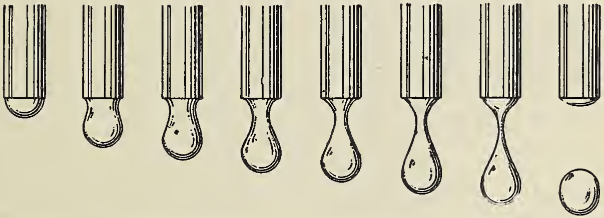


Fig. 112. Some of the stages through which a slowly forming drop passes

The elastic nature of a film is illustrated in Fig. 112, which is from a motion-picture record of some of the stages through which a slowly forming drop passes. The external layers of molecules act like an elastic bag to hold the rest of the liquid within.

Ascension and depression of liquids in capillary tubes. It was shown in Chapter II that in general a liquid stands at the same level in any number of communicating vessels. The following experiments will show that this rule ceases to hold in the case of tubes of small diameter.

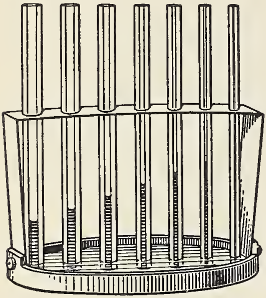


FIG. 113. Rise of liquids in capillary tubes

Arrange a series of capillary tubes of diameter varying from 2 mm to $\frac{1}{4}$ mm as in Fig. 113.

When water or ink is poured into the vessel it will be found to rise higher in the tubes than in the vessel, and it will be seen that the smaller the tube, the greater the height to which the liquid rises. If the water is replaced by mercury, however, the effects will be found to be just inverted. The mercury is depressed in all the tubes, the depression being greater in proportion as the tube is smaller (Fig. 114 (*a*)). This depression is most easily observed with a U-tube like that shown in Fig. 114 (*b*).

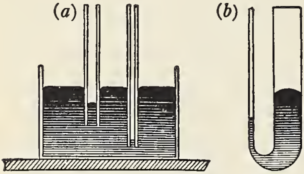


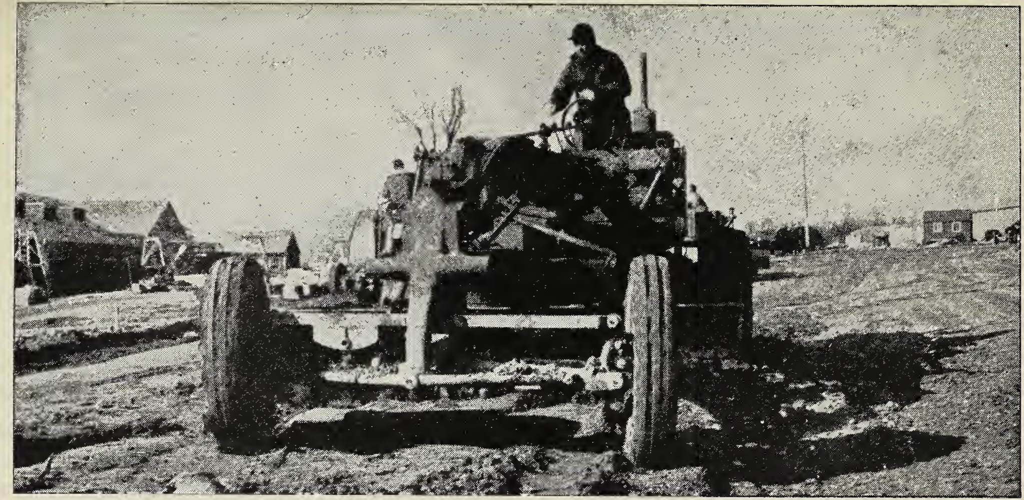
FIG. 114. Depression of mercury in capillary tubes

Experiments have established the following laws:

1. *Liquids rise in capillary tubes when they are capable of wetting them, but are depressed in tubes which they do not wet.*

2. *The elevation in the one case and the depression in the other are inversely proportional to the diameters of the tubes.*

It will be noticed, too, that when a liquid rises, its surface within the tube is concave upward; when it is depressed, its surface is convex upward. This curved surface is called the *meniscus*. In reading the height of a mercury column, always read to the *top* of the meniscus; when reading a water column, read to the *bottom*.



Tractor

The tractor using an internal-combustion engine was developed for agricultural work about 1914. More recently it has been used in construction work and in the present war has been invaluable both in construction work and in hauling heavy equipment. Tractors are of two types, namely, the wheeled type (as shown in the illustration of one at work on a naval construction project) and the track-laying, or caterpillar, type. The modern tractor can exert a pull equal to two thirds of its weight or even better. (Courtesy of U. S. Navy)

Lumbering with a Caterpillar Tractor Company's (Peoria) Diesel Seventy-five

The caterpillar tractor is in reality a land locomotive that continuously lays the track upon which it runs. It is possessed of enormous tractive power and does not slip on ice or snow. This form of tractor is being increasingly used in logging, not only because of its great power, but also because it prevents excessive destruction of the forests and the soil, with the consequent loss of the water which would otherwise be held by the many capillary activities of soil and vegetation. A caterpillar tractor can operate over surprisingly rough ground. Roads need not be built for it

[**Cause of curvature of a liquid surface in a capillary tube.** The surface molecules of the liquid near the walls of the capillary tube are attracted not only to one another but also to the glass of the tube. Whether the liquid will rise or be depressed in the tube depends on the relative size of these two forces of cohesion and adhesion. In understanding the action we must keep in mind two familiar facts: first, that *the surface of a body of water at rest* (*for example, a pond*) *is at right angles to the resultant force* (*that is, gravity*) *which acts upon it*; secondly, that *the force of gravity acting on a minute amount of liquid is negligible in comparison with the cohesive forces acting within the liquid.* (See page 135.)

[Consider, then, a very small body of liquid close to the point *o* (Fig. 115), where water is in contact with the glass wall of the tube. Let the quantity of liquid considered be so minute that the force of gravity acting upon it may be disregarded. The force of *adhesion* of the wall will pull the liquid particles at *o* in the direction *oE*. The force of *cohesion* of the liquid will pull these same particles in the direction *oF*. The resultant of these two pulls on the liquid at *o* will then be represented by *oR* (Fig. 115) in accordance with the parallelogram law of Chapter V. If, then, the resultant *oR* of the adhesive force *oE* and the cohesive force *oF* lies to the left of the vertical *om* (Fig. 116), since the surface of a liquid always assumes a position at right angles to the resultant force, the liquid must rise up against the wall as water does against glass (Fig. 116).

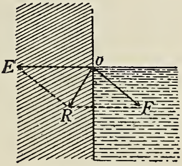


FIG. 115

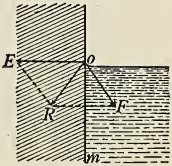


FIG. 116

Condition for elevation of a liquid near a wall

[If the cohesive force *oF* (Fig. 117) is strong in comparison with the adhesive force *oE*, the resultant *oR* will fall to the right of the vertical, in which case the liquid must be depressed about *o*. The liquid does not wet the wall.

Whether, then, a liquid will rise against a solid wall or be depressed by it will depend only on the relative strengths of the adhesion of the wall for the liquid and the cohesion of the liquid for itself. Since mercury does not wet glass, we know that cohesion is here relatively strong, and we should therefore expect that the mercury would be depressed near a glass wall or within a glass tube, as indeed we find it to be. The fact that water will wet glass indicates that in this case adhesion is relatively strong, and hence we should expect water to rise against the walls of the containing vessel, as in fact it does.

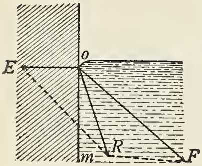


FIG. 117. Condition for the depression of a liquid near a wall

It is clear that a liquid which is depressed near the edge of a vertical solid wall must assume within a tube a surface which is *convex upward*, whereas a liquid which rises against a wall must within such a tube be *concave upward*.

Explanation of ascension and depression in capillary tubes. As soon as the curvatures just mentioned are produced, the

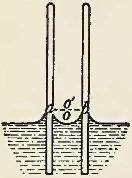


FIG. 118

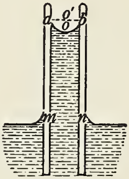


FIG. 119

A concave meniscus causes a rise in a capillary tube

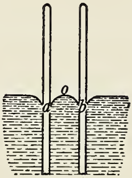


FIG. 120

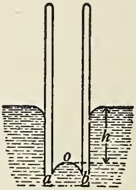


FIG. 121

A convex meniscus causes a fall in a capillary tube

concave surface *aob* (Fig. 118) tends, because of surface tension, to straighten out into the flat surface *ao'b*. But it no sooner thus begins to straighten out than adhesion again elevates it at the edges. It will be seen, therefore, that the liquid must continue to rise in the tube until the weight of

the liquid lifted, namely, *amnb* (Fig. 119), balances the tendency of the surface *aob* to flatten out. The smaller the tube, the higher the liquid will rise, since the weight of the column of liquid to be supported is less. The distance to which liquids will rise in extremely small tubes is astonishing. Water will rise about 10 feet in a glass tube 0.01 millimeter in diameter.

[The convex mercury surface *aob* (Fig. 120) falls until the upward pressure at *o*, due to the depth *h* of mercury (Fig. 121), balances the tendency of the surface *aob* to flatten.

[**Capillary phenomena in everyday life.** Capillary phenomena play a very important part in the processes of nature and of everyday life. After a rain the farmer and the gardener cultivate the surface soil; that is, they stir it up thoroughly to prevent capillary action from bringing the moisture to the surface, where it may evaporate quickly. This keeps the moisture below the surface, where it is of aid to the plants.

[The rise of oil in the wicks of lamps, the complete wetting of a towel when one end of it is allowed to stand in a basin of water, the rapid absorption of coffee by a lump of sugar when only one corner of it is immersed, the rise of sap in trees, the taking up of ink by blotting paper, are all examples of capillary action.

FIG. 122. Insect walking on the surface of water

[**Floating of small objects on water.** Most of us have seen small insects running or walking on the surface of water (Fig. 122), apparently defying the laws of gravitation. Let us study a little more closely this phenomenon.

FIG. 123. Cross section of a floating iron disk loaded with pennies

[From a *flat* and *thin* piece of sheet iron cut a circle from 5 to 6 in. in diameter. Place it carefully on the surface of water. In spite of the fact that iron is nearly eight times as dense as water, it will be found to float (Fig. 123). See how many pennies you can pile gently on the center of the disk before you sink it.

[By use of a bent hairpin or a wire float a needle or a razor blade (Fig. 124). If the needle or blade has been previously magnetized, it may be made to move about in any direction over the surface in obedience to the pull of a magnet held, for example, underneath the table.

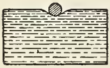


FIG. 124. Cross section of a floating needle

[To discover the cause of this apparently impossible phenomenon, examine closely the surface of the water in the immediate neighborhood of the disk or needle. It will be found to be depressed in the manner shown in Figs. 123 and 124. This furnishes at once the explanation. So long as the needle is so small that its own weight is no greater than the upward force exerted upon it by the tendency of the depressed (and therefore concave) liquid surface to straighten out into a flat surface, the needle cannot sink in the liquid, no matter how great its density. If the water had wet the needle, that is, if it had risen about the needle instead of being depressed, the tendency of the liquid surface to flatten out would have pulled it down into the liquid instead of forcing it upward. Any body about which a liquid is depressed will therefore float on the surface of the liquid if its mass is not too great. Even if the liquid tends to rise about a body when it is perfectly clean, an imperceptible film of oil upon the body will cause it to depress the liquid, and hence to float.

Summary. **Cohesive forces within a free liquid tend to make it assume that form which has the minimum area for a given volume, namely, a sphere. For this reason a liquid film acts like a stretched membrane.**

A liquid wets a solid when at the point of contact of their two free surfaces the force of cohesion and the force of adhesion give a resultant whose direction lies within the solid.

A liquid does not wet a solid when, under the forces mentioned above, the direction of the resultant lies within the liquid.

Liquids which wet capillary tubes rise in them. Liquids which do not wet capillary tubes are depressed in them.

The distances which liquids rise in capillary tubes or are depressed in them are greater the smaller the diameter of the tubes.

QUESTIONS AND PROBLEMS

A

1. The leads for pencils are made by subjecting powdered graphite to enormous pressures produced by hydraulic machines. Explain how the pressure changes the powder to a coherent mass.

2. Explain the watering of flowers by setting the pot in a basin of water.

3. (*a*) Could you write with a pen on blotting paper? (*b*) How does paper made for writing purposes differ from blotting paper?

4. Why will a piece of sharp-cornered glass become rounded when heated to redness in a Bunsen flame?

5. Shot are made by pouring molten lead through a sieve on top of a tall tower and catching it in water at the bottom. Why are the shot spherical?

6. Why does a small stream of water break up into drops instead of falling as a continuous thread?

7. (*a*) Why does a new and oily steel pen not write well? (*b*) Why is it difficult to write on oiled paper?

B

1. Candle grease may be removed from clothing by covering it with blotting paper and then passing a hot flatiron over the paper. Explain.

2. Explain how capillary attraction makes an irrigation system successful.

3. What force is mainly responsible for the return to the surface of the earth of water that has gravitated into the soil? Would the looseness of the soil make any difference in the amount of water which comes to the surface and evaporates? (Dry farming.)

4. Explain how capillary attraction comes usefully into play in the steel pen, camel's-hair brushes, lampwicks, and sponges.

5. Fasten a bit of gum camphor to one end of half a toothpick and lay it upon the surface of a large vessel of clean still water. Explain the motion.

Absorption of Gases by Solids and Liquids

Absorption of gases by solids. Fill a large test tube with ammonia gas by heating aqua ammonia and causing the gas given off to displace mercury in the tube, as in Fig. 125. Heat a piece of charcoal an inch long and nearly as wide as the tube to redness and then plunge it beneath the mercury. When it is cool, slip it underneath the mouth of the test tube and allow it to rise into the gas. The mercury will rise in the tube, as in Fig. 126. Why?

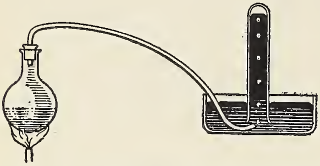


FIG. 125. Filling tube with ammonia

This property of absorbing gases is possessed to a notable degree by porous substances, especially coconut and peach-pit charcoal. Butter which has been kept in the refrigerator for some time often shows by its taste that it has absorbed gases given off by other foods. Many solids hold, closely adhering to their surfaces, thin layers of the gases with which they are in contact; the high absorbing power of porous substances is probably due to their great surface area.

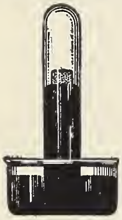


FIG. 126. Absorption of ammonia gas by charcoal

That the same substance exerts widely different attractions upon the molecules of different gases is shown by the fact that charcoal will absorb 90 times its own volume of ammonia gas, 35 times its volume of carbon dioxide, and only 1.7 times its volume of hydrogen. The usefulness of charcoal as a deodorizer is due to its enormous ability to absorb certain kinds of gases. This property makes it available for use in gas masks. The metal palladium when heated in hydrogen can absorb 800 times its own volume.

Absorption of gases in liquids. Slowly heat a beaker containing cold water. Small bubbles of air will be seen to collect in great numbers upon the walls and to rise through the liquid to the surface.

That they are bubbles of air and not of steam is proved, first, by the fact that they appear when the temperature is far below boiling, and, secondly, by the fact that they do not condense as they rise into the higher and cooler layers of the water.

The experiment shows two things: first, that water ordinarily contains considerable quantities of air dissolved in it, and, secondly, that the amount of air thus dissolved decreases as the temperature rises. The first point is also proved by the existence of fish life, for fish obtain from the dissolved air the oxygen needed to support life.

The amount of gas absorbed by water varies greatly with the nature of the gas. At 0° C. and a pressure of 76 centimeters 1 cubic centimeter of water will absorb 1050 cubic centimeters of ammonia, 1.8 cubic centimeters of carbon dioxide, and only .04 cubic centimeter of oxygen. Commercial aqua ammonia is simply ammonia gas dissolved in water.

[The following experiment illustrates the absorption of ammonia by water:

[Fill the flask *F* (Fig. 127) and tube *b* with ammonia by passing a current of the gas in at *a* and out through *b*. Then cork up *a* and thrust *b* into *G*, a flask nearly filled with water colored slightly red by the addition of litmus and a drop or two of acid. As the ammonia is absorbed, the water will slowly rise in *b*, and as soon as it reaches *F* it will rush up very rapidly until the upper flask is nearly full. At the same time the color will change from red to blue because of the action of the ammonia upon the litmus.

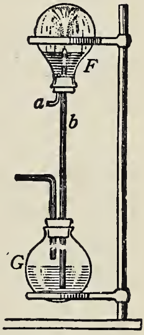


Fig. 127. Absorption of ammonia by water

[Experiment shows that *in every case of absorption of a gas by a liquid or a solid the quantity of gas absorbed decreases with an increase in temperature* — a result which was to have been expected from the kinetic theory, since increasing the molecular velocity must of course increase the difficulty of retaining the gaseous molecules.

Effect of pressure upon absorption. Soda water (or carbonated water) is ordinary water in which large quantities of carbon-dioxide gas have been absorbed. This is accomplished by bringing the water into contact with the gas under high pressure. As soon as the pressure is relieved, the gas passes rapidly out of solution. This is the cause of the characteristic effervescence, or bubbling, of soda water and other carbonated beverages. These facts show clearly that the amount of carbon dioxide absorbed by water is greater for high pressures than for low. As a matter of fact, careful experiments have shown that the amount of any gas absorbed is directly proportional to the pressure; so that if carbon dioxide under a pressure of 10 atmospheres is brought into contact with water, ten times as much of the gas is absorbed as if it had been under a pressure of 1 atmosphere. This is known as Henry's law.

Summary. **The absorbing power of solids and liquids for gases decreases with increase in temperature.**

The quantity of gas absorbed by a liquid is directly proportional to the pressure.

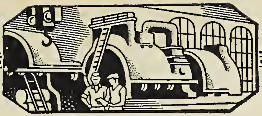
QUESTIONS AND PROBLEMS

1. Water drawn from the faucet often has a "milky" appearance for a few seconds. It rapidly clears. Explain.

2. (*a*) Why are bubbles of air seen clinging to the inner surface of a tumbler containing cold water? (*b*) What difference would a rise in the temperature of the room make in the number and size of the bubbles?

3. Why do fish in a small aquarium without plants die if the water is not frequently renewed?

4. How can you tell whether bubbles that rise from the bottom of a vessel which is being heated are bubbles of air or bubbles of steam?



UNIT THREE

Work and Heat

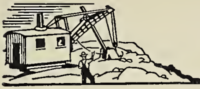
Throughout all the ages, up to a hundred and fifty years ago, practically all man's work was done by means of his own muscles or those of his horse or his ox. Human slaves chained to the benches drove the Roman triremes against the enemy. About two hundred years after the discovery of the laws of force and motion man began for the first time to realize that "work" — a concept that could not be even defined before the discovery of these laws — could be obtained from heat; in other words, that heat was convertible into mechanical energy.

Today practically all the world's heaviest work is done by iron slaves driven by the burning of coal or oil or by the power of falling water. The newly launched *Queen Mary* is driven across the Atlantic by four propellers that have behind them a combined horsepower of nearly 200,000. This means that nearly a million Roman galley slaves would be required to drive the ship at the same rate, and in view of the necessity for shifts the actual required number would be nearer four million.

Enormous social changes have been brought about by the discovery of how to get work out of heat. The conversion of raw materials into finished products was soon removed from the home and concentrated in a relatively few industrial centers. Great new industries were created, of which the telephone industry, the lighting industry, the oil industry, the automobile industry,

each supporting millions of people, are illustrations. The daily output of one man was often multiplied manyfold, and he was able to have luxuries never before dreamed of.

This third unit of physics deals, then, with how heat is measured; what effects it produces in solids, liquids, and gases; how it is transformed into work; and how it is practically applied in modern life. And it is in this unit that the principle of the conservation of energy — the most far-reaching generalization of modern science — is fully explained.



CHAPTER VII

Work and Mechanical Energy*

Definition and Measurement of Work

Definition of work. Ordinarily when we think of work we think of something involving either mental or physical activity; but from the standpoint of physics and engineering work is done only when a force moves the body on which it acts through a definite distance. The amount of the work accomplished is measured by the product of the force acting and the distance through which it moves the point of application. Thus, if 1 gram of mass is lifted 1 centimeter in a vertical direction, 1 gram of force has acted, and the distance through which it has acted is 1 centimeter. We say, therefore, that the lifting force has accomplished 1 *gram-centimeter* of work. If the gram of force had lifted the body upon which it acted through 2 centimeters, the work done would have been 2 gram-centimeters; if a force of 3 grams had acted and the body had been lifted through 3 centimeters, the work done would have been 9 gram-centimeters; etc. Or, in general, if W represents the work accomplished, F the value of the acting force, and s the distance through which its point of application moves, then *the definition of work is given by the equation*

$$W = F \times s. \tag{1}$$

In the scientific sense no work is ever done unless the force succeeds in *producing motion* in the body on which it acts.

* It is recommended that this chapter be preceded by an experiment in which the student investigates for himself the law of the lever, that is, the principle of moments (see, for example, Experiment 15 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis), and that it be accompanied by a study of the principle of work as exemplified in at least one of the other simple machines (see, for example, Experiment 17 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis).

A pillar supporting a building does no work; a man tugging at a stone but failing to move it does no work. In the popular sense we sometimes say that we are doing work when we are simply holding a weight or doing anything else which results in fatigue; but in physics the word *work* is used to describe not the effort put forth but the *effect accomplished,* as represented in equation (1).

Units of work. There are two common units of work in the metric system: the *gram-centimeter* and the *kilogram-meter.* As the names imply, the gram-centimeter is the work done by a force of 1 gram when it moves the point on which it acts 1 centimeter. The kilogram-meter is the work done by a kilogram of force when it moves the point on which it acts 1 meter. The *gram-meter* also is sometimes used.

Corresponding to the English unit of force, the pound, is the unit of work, the *foot-pound.* This is the work done by a "pound of force" when it moves the point on which it acts 1 foot.

In the absolute system of units the dyne is the unit of force, and the dyne-centimeter, or *erg,* is the corresponding unit of work. The erg is the amount of work done by a force of 1 dyne when it moves the point on which it acts 1 centimeter. To raise 1 liter of water from the floor to a table 1 meter high would require $1000 \times 980 \times 100 = 98{,}000{,}000$ ergs of work. It will be seen, therefore, that the erg is an exceedingly small unit. For this reason it is customary to employ a larger unit which is equal to 10,000,000 ergs. It is called a *joule* in honor of the great English physicist James Prescott Joule (1818–1889). The work done in lifting a liter of water 1 meter is therefore 9.8 joules.

Summary. **Work = force times distance; that is,**

$$W = F \times s.$$

Gravitational units of work are the gram-centimeter (g-cm), the gram-meter (g-m), the kilogram-meter (kg-m), the foot-pound (ft-lb), and the foot-ton (ft-t).

Absolute units of work are the dyne-centimeter, or erg, and the joule (= 10,000,000 ergs).

QUESTIONS AND PROBLEMS

A

1. Define work, and give two examples.

2. Give two examples in which no work is done, but merely effort is exerted.

3. Name and define three units in which work is measured.

4. How much work would be done by you in walking up a flight of stairs 10 ft. in height?

5. A carpenter pushed 5 lb on his plane while taking off a shaving 4 ft long. How much work was done?

6. A woman in cleaning a rug moved the nozzle of a vacuum cleaner a total distance of 130 ft, using an average force of $\frac{1}{2}$ lb. How much work did she do?

7. To drag a trunk weighing 120 lb required a force of 40 lb. (*a*) How much work would be required to drag this trunk 2 yd? (*b*) to lift it 2 yd vertically?

B

1. A certain powerful machine exerted an average force of 36 t in punching rivet holes in a sheet of steel 1 in. thick. Calculate (*a*) the number of foot-tons of work done in punching one hole; (*b*) the number of foot-pounds of work.

2. (*a*) Why is less work done in stretching a steel rod to a tension of 2000 lb than in stretching a coiled spring to the same tension? (*b*) Does the same reasoning which applies to this question prove that it is safer to test a boiler with water than with compressed air? Explain.

3. A horse pulls a metric ton of coal to the top of a hill 30 m high. Express the work accomplished in kilogram-meters. (A metric ton = 1000 kg.)

4. A steel bar of uniform cross section is 20 ft long and weighs 100 lb. How much work is required to lift it from a horizontal to a vertical position, one end being kept always on the ground?

5. If the 20,000 inhabitants of a city use an average of 20 l of water per capita per day, how many kilogram-meters of work must the engines do per day if the water has to be raised to a height of 75 m?

Work Expended upon, and Accomplished by, a System of Pulleys

Work and machines in general. Early man in the struggle for existence had nothing but his own muscular forces to aid him in doing his work. Gradually he developed devices for extending these forces and was able to survive in his incessant struggle against the forces of nature and the wild animals all about him. Gradually he extended his activities to the sea, to the air, and underground. The complicated machines of today employ in many forms the simple machines which will be studied briefly in the succeeding paragraphs.

Usually these machines multiply the force that man himself is able to exert, but they may also be used to change the direction of the applied force, to increase speed, and to transmit force from one place to another.

FIG. 128. The single fixed pulley

The single fixed pulley. Overcome the force of the earth's attraction upon a mass R by pulling upon a spring balance S, in the manner shown in Fig. 128, until R moves slowly upward. If R is 100 g, the spring balance will also be found to register a force of 100 g, if there is no friction in the pulley.

This experiment shows that in the use of the single fixed pulley the acting force, or effort, E, producing the motion, is equal to the resisting force, or resistance, R, opposing the motion.

Again, since the length of the string is always constant, the distance s through which the point A, at which E is applied, must move is always equal to the distance s' through which the weight R is lifted. Hence, if we consider the work put into the system at A, namely, $E \times s$, and the work accomplished by the system at R, namely, $R \times s'$, we find, obviously, since $R = E$ and $s = s'$, that

$$E \times s = R \times s'; \qquad (2)$$

that is, in the case of the single fixed pulley *the work done by the acting force E (the effort) is equal to the work done against the resisting force R (the resistance)*, or the work *put into* the machine at A is equal to the work *accomplished by* the machine at R.

The single movable pulley. By a single movable pulley overcome the force of the earth's attraction upon the mass R, as shown in Fig. 129. Since the weight of R (R representing in this case the weight of both pulley and suspended mass) is now supported half by the strand C and half by the strand B, the force E acting at A to hold the weight in place, or to move it slowly upward if there is no friction, should be only half of R. A reading of the balance will show that this is the case when due allowance is made for the weight of the pulley.

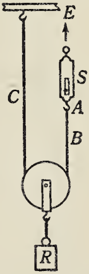


FIG. 129. The single movable pulley

Experiment thus shows that *in the case of the single movable pulley the effort E is just half as great as the resistance R.*

But when we again consider the *work* which the force E must do to lift the weight R a distance s', we see that A must move upward 2 inches in order to raise R 1 inch; for when R moves up 1 inch, both the strands B and C must be shortened 1 inch. As in the case of the fixed pulley, therefore, since $R = 2E$ and $s' = \frac{1}{2}s$,

$$E \times s = R \times s';$$

that is, in the case of the single movable pulley also *the work put into the machine by the effort E is equal to the work accomplished by the machine against the resistance R.*

Combination of pulleys. To overcome a large resistance workmen frequently use a combination of pulleys called a block and tackle, such as either of those shown in Fig. 130.

Lift a weight R by means of such a system of pulleys as is shown in Fig. 130, either (*a*) or (*b*). Here, since R is supported by 6 strands of the cord, it is clear that the force which must be applied at A to hold R in place, or to make it move slowly upward if there were no friction, should be but $\frac{1}{6}$ of R.

The experiment will show this to be the case if the effects of friction, often very considerable, are eliminated by taking the mean of the forces which must be applied at E to cause it to move first slowly upward and then slowly downward. The law of any combination of movable pulleys may then be stated thus: *If n represents the number of strands between which the weight is divided,*

$$\frac{R}{E} = n. \tag{3}$$

But when we again consider the work which the force E must do to lift the weight R through a distance s', we see that, in order that the weight R may be moved up through 1 inch, each of the strands must be shortened 1 inch, and hence the point A must move through n inches; that is, $s' = s/n$. Hence, ignoring friction, in this case also we have

$$E \times s = R \times s';$$

that is, although the effort E is only $1/n$ of the resistance R, *the work put into the machine by the effort E is equal to the work accomplished by the machine against the resistance R.*

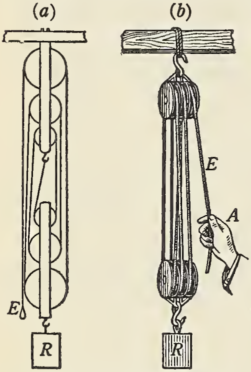


FIG. 130. Combinations of pulleys

Mechanical advantage. The preceding experiments show that by applying a small force E it is sometimes possible to overcome a much larger resisting force R. *The ratio of the resistance R to the effort E (friction being ignored) is called the mechanical advantage of the machine.* Thus the mechanical advantage of the single fixed pulley is 1, that of the single movable pulley is 2, that of the system of pulleys shown in Fig. 130 is 6, etc.

In practice, since in all machines friction exists in varying amounts, the advantage actually derived from the machine

will be less than the theoretical value as obtained by the ratio given above.

If the acting force is applied at R instead of at E, the mechanical advantage of the systems of pulleys of Fig. 130 is $\frac{1}{6}$, for it requires an application of 6 pounds at R to lift 1 pound at E. But it will be observed that the resisting force at E now moves six times as fast and six times as far as the acting force at R. *We can thus either sacrifice speed to gain force or sacrifice force to gain speed*, but in every case whatever we gain in the one we lose in the other.

Summary. **Man uses machines to make his work easier.**

In ideal frictionless pulley systems the work expended on the system by the effort E equals the work accomplished by the system against the resistance R.

The mechanical advantage of any machine is the ratio of the resistance R to the effort E when friction is ignored; that is,

$$\text{M.A.} = \frac{R}{E}.$$

If R is greater than E, speed is lost to gain force; if R is less than E, force is lost to gain speed.

The mechanical advantage of a pulley system using one continuous rope equals the number of strands actually supporting the weight; that is,

$$\frac{R}{E} = n.$$

QUESTIONS AND PROBLEMS

A

1. Two men, pulling 50 lb each, lifted 300 lb by a system of pulleys. Assume that there was no friction; how many feet of rope did they pull down in raising the weight 20 ft?

2. The fixed pulley (*mechanical advantage* = *1*) is extensively used in connection with clotheslines, awnings, and flags. Explain.

3. Diagram a system of six pulleys which will allow an effort of 100 lb to overcome a resistance of 600 lb.

4. A system of pulleys is arranged so that the point at which the effort is applied moves 4 ft when the load is lifted 1 ft. What is the mechanical advantage?

B

1. Can a man pull an automobile out of a ditch more easily with a block and tackle if he pulls in the same direction as that in which the automobile is moving, or if he reverses the block and tackle and pulls in the opposite direction? (See Fig. 131.) Explain.

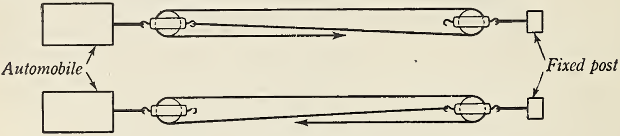


FIG. 131. Two ways to use a block and tackle

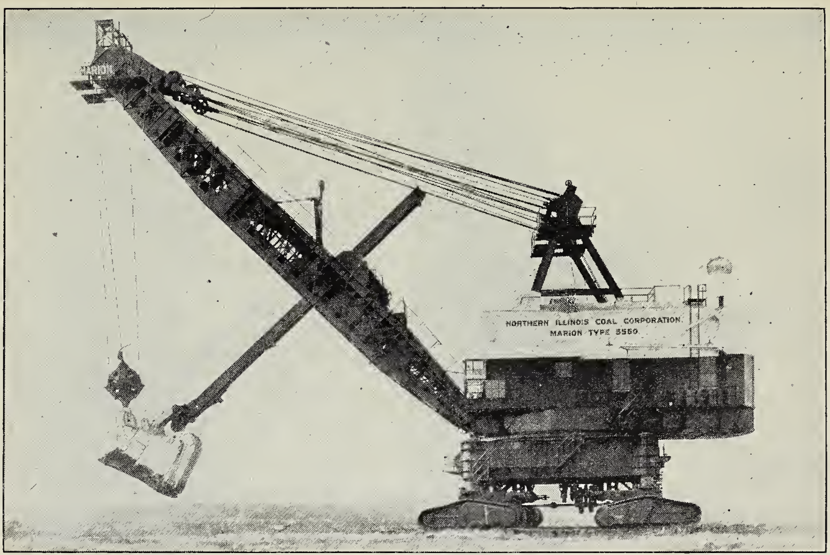
2. (*a*) Represent by a diagram a system of pulleys consisting of a double fixed block and a single movable block. (*b*) How great a weight can be balanced by a force of 30 lb applied to the free end of the rope?

3. A piano was hoisted by means of a movable block having two pulleys and a fixed block having three pulleys. (*a*) Represent by a diagram the system of pulleys. (*b*) What is the mechanical advantage of the system?

Work and the Lever

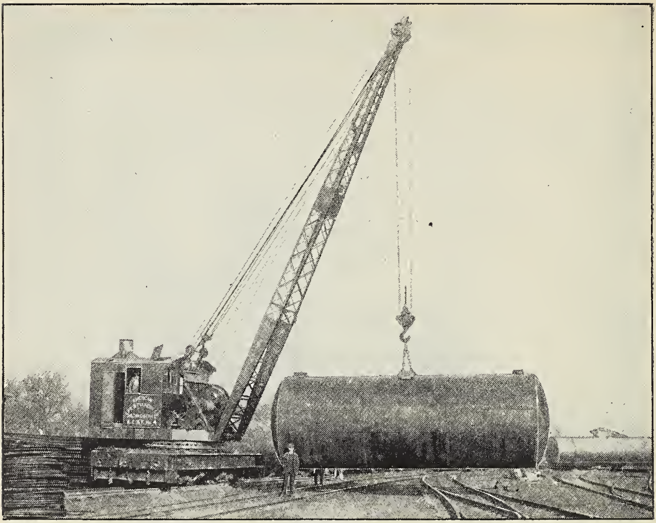
The lever. The lever (Fig. 132) is the simplest and probably the oldest of the machines. Somewhere back in dim antiquity some savage ancestor discovered, perhaps to his surprise, that he could use a sapling to pry a stone out of the ground or to move some object which he could not otherwise reach. We use oars, shears, brooms, automobile brake pedals, and many variations of these to do work with less effort or with greater speed.

The law of the lever. The lever may be considered as a rigid rod free to turn about some fixed point *P* called the fulcrum (Fig. 132). This tendency to turn depends upon two things, the amount of force acting and its distance from the fulcrum. Naturally if the force were larger, the bar would turn more easily; and if the force were moved farther out



A Giant Electric Shovel, the Most Human of Machines

It digs like a Titan, and is used for all kinds of excavating. It is simply a combination of levers and pulleys. The picture shows the largest shovel in the world. The dipper has a capacity of 32 cubic yards. It picks up 100,000 pounds of earth at a bite. An automobile can be driven into the shovel. (Courtesy of the Marion Shovel Company)



Locomotive Cranes

Locomotive cranes — again merely combinations of levers and pulleys. The lower one is an enormous wrecking crane; it can be operated by one man; it can lift more than 200 tons; it replaces a crew of 50 men; it is moved from place to place by its own engine. It is shown here hoisting another locomotive crane. (Courtesy of the Orton Crane and Shovel Company)

from the fulcrum, it would have a greater tendency to produce rotation. This tendency to produce rotation is called the moment of the force; and its magnitude is measured by the product of the force times the force arm, the force arm being the perpendicular distance from the fulcrum to the line of direction of the force. (See Fig. 133.)

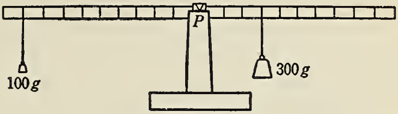


FIG. 132. The single lever

First balance a meter stick as in Fig. 132, then hang a mass of, say, 300 g by a thread from a point 15 cm from the fulcrum. Then find a point on the other side of the fulcrum at which a weight of 100 g will just balance the 300 g. This point will actually be found to be 45 cm from the fulcrum. It will be seen at once that the product of 300 × 15 is equal to the product of 100 × 45.

Next find the point at which 150 g just balances the 300 g. This will be found to be 30 cm from the fulcrum. Again the products, 300 × 15 and 150 × 30, are equal.

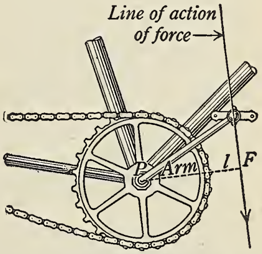


FIG. 133. The moment of the force of the rider's foot is the force times the arm, $F \times l$

No matter where the weights are placed or what weights are used on either side of the fulcrum, if the lever is balanced the product of the effort E by its distance l from the fulcrum (Fig. 134) will be found to be equal to the product of the resistance R by its distance l' from the fulcrum.

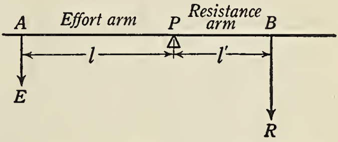


FIG. 134. Illustrating the law of moments, namely, $El = Rl'$

These experiments on the lever may, then, be generalized in the following law: *The moment of*

the effort is equal to the moment of the resistance. Algebraically stated, it is

$$El = Rl'. \tag{4}$$

It will be seen that the *mechanical advantage* of the lever, namely R/E, is equal to l/l', that is, to *the lever arm of the effort divided by the lever arm of the resistance.*

General laws of the lever. If parallel forces are applied at several points on a lever, as in Figs. 135 and 136, it will be found, in the particular cases illustrated, that for equilibrium

$$200 \times 30 = 100 \times 20 + 100 \times 40,$$

and $$300 \times 20 + 50 \times 40 = 100 \times 15 + 200 \times 32.5;$$

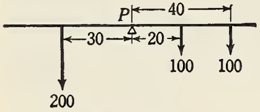


FIG. 135

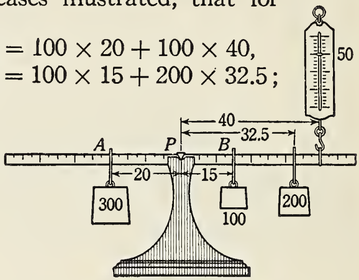


FIG. 136

Condition of equilibrium of a bar acted upon by several forces

that is, *the sum of all the moments which are tending to turn the lever in one direction about any axis is equal to the sum of all the moments tending to turn it in the opposite direction.*

If we support the levers of Figs. 135 and 136 by spring balances attached at P, we shall find, after allowing for the weight of the stick, that the two forces indicated by the balances are, respectively, $200 + 100 + 100 = 400$ and $300 + 100 + 200 - 50 = 550$; that is, *the sum of all the forces acting in one direction on the lever is equal to the sum of all the forces acting in the opposite direction.*

The weight of the lever. To simplify the preceding discussion the weight of the lever bar itself has been ignored. In actual practice, however, this weight must be considered unless the fulcrum is placed directly under the center of gravity of the bar. In all other cases the weight of the bar is

taken as though concentrated as a single force at the center of gravity of the bar, and its moment added to the other moments tending to produce rotation in the same direction.

Work expended upon and accomplished by the lever. We have just seen that when the lever is in equilibrium — that is, when it is *at rest* or is *moving uniformly* — the relation between the effort E and the resistance R is shown in the equation of moments, namely $El = Rl'$. Let us now suppose, precisely as in the case of the pulleys, that the force E raises the weight R through a small distance s'. To accomplish this the point A to which E is attached must move through a distance s (Fig. 137). From the similarity of the triangles APn and BPm it will be seen that l/l' is equal to s/s'. Hence equation (4), which represents the law of the lever and which may be written $E/R = l'/l$, may also be written in the form

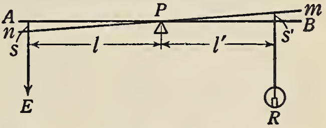


FIG. 137. Showing that the equation of moments, $El = Rl'$, is equivalent to $Es = Rs'$

$$\frac{E}{R} = \frac{s'}{s}, \text{ or } Es = Rs'.$$

Now Es represents the work done by the effort E, and Rs' the work done against the resistance R. Hence the law of moments, which has just been found by experiment to be the law of the lever, is equivalent to the statement that *whenever work is accomplished by the use of the lever, the work expended upon the lever by the effort E is equal to the work accomplished by the lever against the resistance R.*

The three classes of levers. It is customary to divide levers into three classes, as follows:

1. In levers of the first class the fulcrum P is between the acting force E and the resisting force R (Fig. 138). The mechanical advantage of levers of this class is greater or less than 1 according as the lever arm l of the effort is greater or less than the lever arm l' of the resistance.

2. In levers of the second class the resistance R is between the effort E and the fulcrum P (Fig. 139). Here the lever arm of the effort, that is, the distance from E to P, is necessarily greater than the lever arm of the resistance, that is, the distance from R to P. Hence the mechanical advantage of levers of the second class is always greater than 1.

3. In levers of the third class the acting force is between the resisting force and the fulcrum (Fig. 140). The mechanical

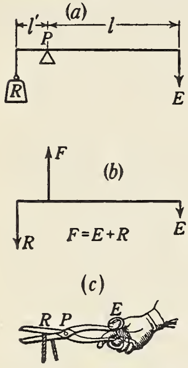


FIG. 138. Levers of first class

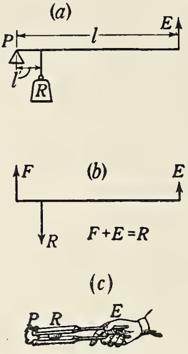


FIG. 139. Levers of second class

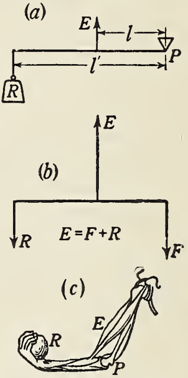


FIG. 140. Levers of third class

advantage is then obviously less than 1; that is, in this type of lever force is always sacrificed for the sake of gaining speed.

In all these cases the force F exerted upon the lever by the fulcrum P may be found by the relation stated on page 158.

Summary. **The moment of a force is the force times its lever arm. The lever arm is the perpendicular distance from the axis of rotation to the line of action of the force.**

Law of the simple lever. **The moment of the effort equals the moment of the resistance; that is, $El = Rl'$.**

General law of the lever. **(1) The sum of all the moments tending to turn the lever in one direction about any axis is equal to the sum of all the moments tending to turn it in the opposite direction;**

(2) the sum of all the forces acting in one direction on the lever is equal to the sum of all the forces acting in the opposite direction.

In the ideal lever the work expended on the lever by the effort equals the work accomplished by the lever against the resisting force.

QUESTIONS AND PROBLEMS

[It is suggested that the student, before attempting to solve a lever problem, should construct a simple diagram, approximately to scale, showing the magnitude of the forces, their points of application, their direction, and the distances of the forces from the fulcrum.]

A

1. Explain the principle of weighing by the steelyards (Fig. 141). What must be the weight of the bob P if at a distance of 40 cm from the fulcrum O it balances a weight of 10 kg placed at a distance of 2 cm from O?

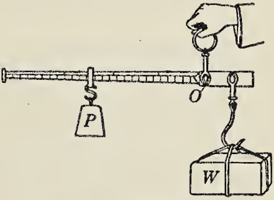


FIG. 141. Steelyards

2. Why do tinners' shears have long handles and short blades and tailors' shears just the opposite?

3. Locate the effort, resistance, and fulcrum in each of the following applications of the lever principle: (*a*) a broom; (*b*) the human arm; (*c*) a wheelbarrow; (*d*) the oar of a rowboat; (*e*) the clutch pedal of an automobile (Fig. 142); (*f*) a hammer pulling a nail.

4. If you knew your own weight, how could you determine the weight of a companion if you had only a teeterboard (a seesaw) and a foot rule?

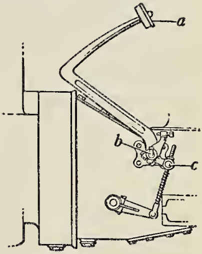


FIG. 142. Automobile clutch

5. Two boys are carrying a bag of walnuts at the middle of a long stick. Will it make any difference whether they walk close to the bag or farther away, so long as each is at the same distance from it?

6. Two boys carry a load of 60 lb on a pole between them. If the load is 4 ft from one boy and 6 ft from the other, how many pounds does each boy carry? (Consider the

force exerted by one of the boys as the effort, the load as the resistance, and the second boy as the fulcrum.)

7. One end of a piano must be raised to remove a broken caster. The force required is 240 lb. Make a diagram to show how a 6-foot steel bar may be used as a second-class lever to raise the piano with an effort of 40 lb.

8. A lever is 3 ft long. Where must the fulcrum be placed so that a weight of 300 lb at one end shall be balanced by 50 lb at the other?

B

1. A balance has unequal arms, the left-hand arm having a length 99 per cent of that of the right-hand arm. A dealer has the habit of putting in the left-hand pan the articles which he sells. Who gains, the dealer or the customer? Why?

2. Copy Figure 142, adding to it the probable direction of the effort and of its lever arm.

3. Two men lift a small 40-foot telegraph pole weighing 400 lb. The center of gravity of the pole is 16 ft from one end. How many pounds are supported by each man, it being assumed that the pole is grasped at its extremities?

4. By a series of diagrams (see Fig. 133) explain how the moment of the force of a bicycle-rider's foot passes from zero to a maximum and then to zero at each downward movement, or half-revolution, of his foot.

5. A telephone pole 40 ft long balanced horizontally over a support placed 10 ft from the thick end. When the support was placed under the pole 15 ft from the thick end, it balanced when a workman weighing 160 lb applied his full weight at the small end. Find the weight of the pole.

6. A stick 3 ft long rests across the shoulder of a man, 1 ft of its length extending to the rear of the shoulder. On this end hangs a 10-pound bundle. (*a*) Find the downward force of the hand at the 2-foot end balancing the bundle. (*b*) Find the force of the shoulder upward against the stick, neglecting the weight of the stick. (*c*) What would have been the upward force of the shoulder had 2 ft of the stick extended to the rear?

7. How would you arrange a crowbar to use (*a*) as a lever of the first class in overturning a heavy object? (*b*) as a lever of the second class?

8. A uniform plank 20 ft long, weighing 200 lb, rests on a flat roof with 8 ft of its length projecting beyond the edge of the roof. If a keg of nails weighing 50 lb rests over a point 1 ft from the inner end, how far out on the plank beyond the edge of the roof may a man weighing 180 lb go without tipping the plank?

9. If the ball of the float valve (Fig. 143) has a diameter of 10 cm and if the distance from the center of the ball to the pivot

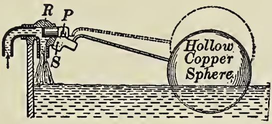


FIG. 143

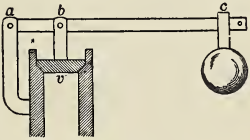


FIG. 144

S is 20 times the distance from S to the pin P, with what force is the valve R held shut when the ball is half immersed? (Neglect weight of ball.) (Volume of a sphere $= \frac{4}{3}\pi r^3$.)

10. A safety valve and weight are arranged as in Fig. 144. If ab is $1\frac{1}{2}$ in. and bc $10\frac{1}{2}$ in., what effective steam pressure per square inch is required on the valve to unseat it, if the area of the valve is $\frac{1}{2}$ in.^{2} and the weight of the ball 4 lb?

11. The hay scales shown in Fig. 145 consist of a compound lever with fulcrums at F, F', F'', F'''. If Fo and $F'o'$ are lengths of 6 in., FE and $F'E$ 5 ft, $F''n$ 1 ft, $F''m$ 6 ft, rF''' 2 in., and $F'''S$ 20 in., how many pounds at W will be required to balance a weight of a ton on the platform?

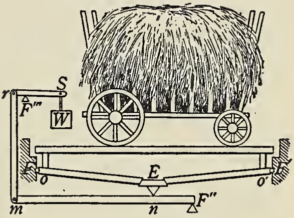


FIG. 145

The Principle of Work

Statement of the principle of work. The study of pulleys led us to the conclusion that in all cases where such machines are used the work done by the effort is equal to the work done against the resistance, provided always that friction

may be neglected and that the motions are uniform so that none of the force exerted is used in overcoming inertia. The study of levers led to precisely the same result. In Chapter II the study of the hydraulic press showed that the same law applied in this case also, for it was shown that the force on the small piston times the distance through which it moved was equal to the force on the large piston times the distance through which it moved. Similar experiments upon all sorts of machines have shown that the following is an absolutely general law: *In all mechanical devices of whatever sort, in all cases where friction may be neglected or eliminated, the work expended upon the machine is equal to the work accomplished by it.*

This important generalization, called *the principle of work*, was first stated by Newton in 1687. It has proved to be one of the most fruitful principles ever put forward in the history of physics. By its application it is easy to deduce the relation between the force applied and the force overcome in any sort of machine, provided only that friction is negligible and that the motions take place slowly. It is only necessary to produce or to imagine a displacement at one end of the machine and then to measure or calculate the corresponding displacement at the other end. The ratio of the second displacement to the first is the ratio of the force acting to the resistance overcome.

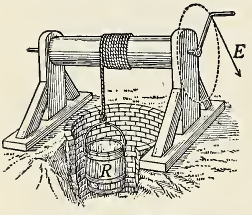


FIG. 146. A well windlass — a form of wheel and axle

The wheel and axle. This simple machine (Figs. 146 and 147) may be considered as a modified form of the lever. The effort is applied at the circumference of the wheel A (Fig. 147) which winds the rope on the circumference of the axle C so as to raise the weight R. The effort arm is AC, and the resistance arm is BC, the point C being considered as the fulcrum. The capstan used for hoisting the anchor of a ship, the windlass used for hoisting

water from wells, and the steering wheel on motor boats are all practical examples of the wheel-and-axle principle.

Let us apply the principle of work to discover the law of the wheel and axle. When the large wheel has made one revolution, the point A (Fig. 147) on the rope moves down a distance equal to the circumference of the wheel. During this time the weight R is lifted a distance equal to the circumference of the axle. Hence the equation $Es = Rs'$ becomes $E \times 2\pi r_w = R \times 2\pi r_a$, where r_w and r_a are the radii of the wheel and axle respectively. This equation may be written in the form

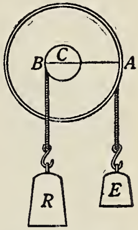


FIG. 147. The wheel and axle

$$\frac{R}{E} = \frac{r_w}{r_a}; \qquad (5)$$

that is, *the weight lifted on the axle is as many times the force applied to the wheel as the radius of the wheel is times the radius of the axle.* Otherwise stated, *the mechanical advantage of the wheel and axle is equal to the radius, diameter, or circumference of the wheel divided by the radius, diameter, or circumference of the axle.*

The principle of work applied to the inclined plane. A driver desiring to raise a heavy barrel from the ground into his truck may be able to lift it bodily. In such a case the work done would be equal to the product of the weight of the barrel times the vertical distance from the ground to the truck. If, however, he is unable to exert enough force to lift the barrel in this way, he may, by using a much smaller effort, roll it up a long plank into the truck. Has he done any less work by using the inclined plane?

The work done against gravity in lifting a weight R (Fig. 148) from the bottom to the top of a plane is evidently equal to R times the height h of the plane. But the

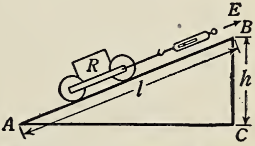


FIG. 148. The inclined plane

work done by the acting force E while the carriage of weight R is being pulled from the bottom to the top of the plane is equal to E times the length l of the plane. Hence the principle of work gives

$$El = Rh, \text{ or } \frac{R}{E} = \frac{l}{h}; \tag{6}$$

that is, *the mechanical advantage of the inclined plane, or the ratio of the weight lifted to the force acting parallel to the plane, is equal to the ratio of the length of the plane to the height of the plane.* This is precisely the conclusion at which we arrived in another way in Chapter V, p. 91.

The screw. When a building is to be lifted, it is necessary to have a device with a much higher mechanical advantage than any of the machines just described. A screw such as the jackscrew shown in Fig. 149 may be used for this purpose.

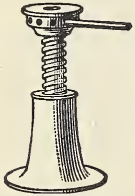


FIG. 149. The jackscrew

The screw is a combination of the inclined plane and the lever. Its law is easily obtained from the principle of work. When the force which acts on the end of the lever has moved this point through one complete revolution, the weight R, which rests on top of the screw, has evidently been lifted through a vertical distance equal to the distance between two adjoining threads. This distance d is called the *pitch* of the screw. Hence, if we represent by l the length of the lever, for one complete revolution the principle of work gives

$$E \times 2\,\pi l = Rd, \quad \text{or} \quad \frac{R}{E} = \frac{2\,\pi l}{d}; \tag{7}$$

that is, *the mechanical advantage of the screw, or the ratio of the weight lifted to the force applied, is equal to the ratio of the circumference of the circle moved over by the end of the lever to the distance between the threads of the screw.* In actual practice the friction in such an arrangement is always very great, so that the effort exerted must always be considerably greater than that given by equation (7). The common jackscrew

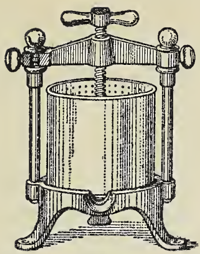


FIG. 150. The fruit-jelly or lard press

just described (used chiefly for raising buildings), the turnbuckle, the automobile jack, the lard press (Fig. 150), the micrometer-screw caliper for measuring minute distances, and the vise (Fig. 151) are all familiar forms of the screw. The bolts and screws used daily by carpenters and mechanics are applications of this machine.

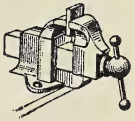


FIG. 151. The vise

A train of gears. One common form of machine capable of very high mechanical advantage is the train of gear wheels shown in Fig. 152. Let the student show from the principle of work, namely $Es = Rs'$, that the mechanical advantage, that is, R/E, of such a device is

$$\frac{\text{Circumference of } a}{\text{Circumference of } e} \times \frac{\text{number of cogs in } d}{\text{number of cogs in } c} \times \frac{\text{number of cogs in } f}{\text{number of cogs in } b}. \tag{8}$$

The worm wheel. Another device of high mechanical advantage is the worm wheel (Fig. 153). Show that if l is the

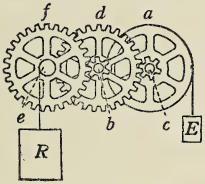


FIG. 152. Train of gear wheels

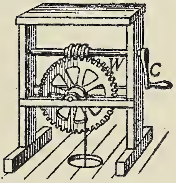


FIG. 153. The worm wheel

length of the crank arm C, n the number of teeth in the cogwheel W, and r the radius of the axle, the mechanical advantage is given by

$$\frac{R}{E} = \frac{2\,\pi l n}{2\,\pi r} = n\frac{l}{r}. \tag{9}$$

This device is used most frequently when the primary object is to decrease speed rather than to multiply force. It will be seen that the crank handle must make n turns while the cogwheel is making one. The worm-gear drive is generally used in the rear axles of motor trucks.

The differential pulley. In the differential pulley (Fig. 154) an endless chain passes first over the fixed pulley A, then down and around the movable pulley C, then up again over the fixed pulley B, which is rigidly attached to A but differs slightly from it in diameter. On the circumference of all the pulleys are projections which fit between the links and thus keep the chains from slipping. When the chain is pulled down at E, as in Fig. 154 (b), until the upper rigid system of pulleys has made one complete revolution, the chain between the upper and lower pulleys has been shortened by the difference between the circumferences of the pulleys A and B, for the chain has been pulled up a distance equal to the circumference of the larger pulley and let down a distance equal to the circumference of the smaller pulley. Hence the load R has been lifted by half the difference between the circumferences of A and B. The mechanical advantage is therefore equal to the circumference of A divided by half the difference between the circumferences of A and B.

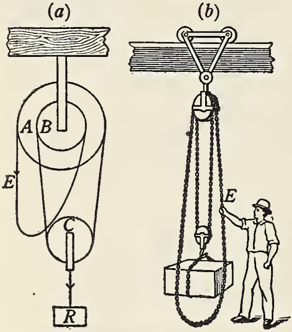


Fig. 154. The differential pulley

Summary. Newton's principle of work. **In all mechanical devices of whatever sort, if friction may be neglected, the work expended upon the machine is equal to the work accomplished by it.**

QUESTIONS AND PROBLEMS

[In all the following problems friction is to be neglected.]

A

1. Name two or three household appliances whose mechanical advantage is less than 1.

2. Analyze several types of manual labor (such, for instance, as messenger service, digging in hard soil and soft soil, chopping or sawing wood, running a lawn-mower, gathering in a farm crop, etc.) and see if the definition ($W = Fs$) holds for each. Is not $F \times s$ the thing *paid for* in every case?

3. Tabulate five simple machines, giving the formula for the particular mechanical advantage of each.

4. What simple machines do you see in the screwdriver, brace and bit, lower jawbone, machine bolt, sewing machine, bicycle, sugar tongs, chisel, and meat-grinder?

5. A force of 80 kg on a wheel whose diameter is 3 m balances a weight of 150 kg on the axle. Find the diameter of the axle.

6. A 1500-pound safe must be raised 5 ft. The force which can be applied is 250 lb. What is the shortest inclined plane which can be used for the purpose?

B

1. The pitch of the screw of a vise (Fig. 151) is 0.2 in., and the handle is 8 in. long. If a force of 40 lb is exerted at the end of the handle, what force is exerted by the jaws?

2. The steering wheel of an automobile is 20 in. in diameter, and the shaft to which it is attached is 2 in. in diameter. How much resistance is overcome when a force of 10 lb is applied to the wheel in steering?

3. A 300-pound barrel was rolled up a plank 12 ft long into a doorway 3 ft high. What force was applied parallel to the plank?

4. In the windlass of Fig. 155 the crank handle has a length of 2 ft, and the barrel a diameter of 8 in. There are 20 cogs in the small cogwheel and 60 in the large one. What is the mechanical advantage?

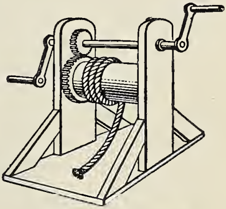


FIG. 155. Windlass with gears

5. A small jackscrew has 20 threads to the inch. Using a lever $3\frac{1}{2}$ in. long will give what mechanical advantage?

6. The screw of a lard press has 5 threads to the inch, and the length of each handle is 6 in. If there were no friction, what force would result from a rotating force of 10 lb applied to the end of each handle? (See Fig. 150.)

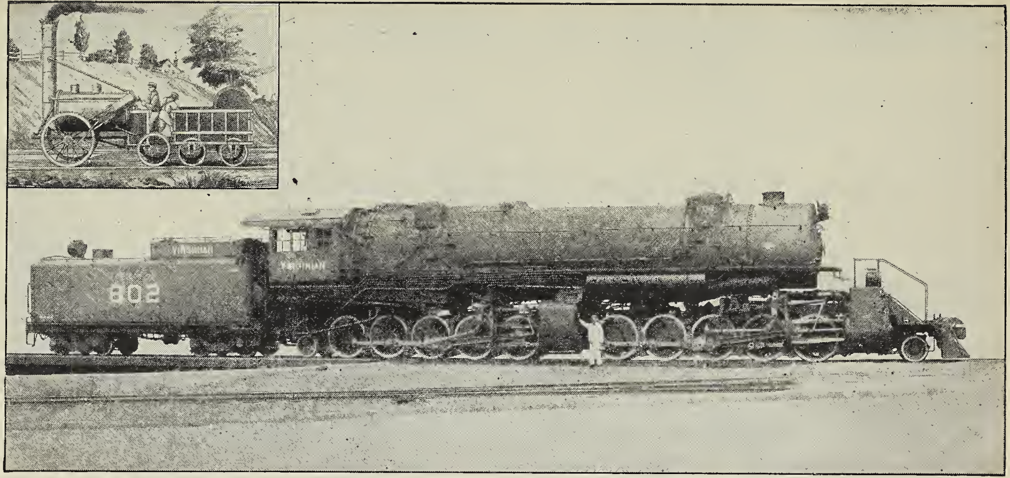
Power and Energy

Definition of power. Up to this time we have discussed the output of machines simply in terms of the work done, measured by the product of the resistance overcome and the distance through which it was moved. To the user, however, one machine may be more valuable than another because *in the same amount of time* it can do *more* work than some other machine.

Let us suppose that a boy and a man were each sent to load a cart with sand. Although the boy may have been three times as many minutes in loading his cart as was the man, the boy nevertheless performed the same amount of work as did the man, for in loading his cart he raised an equal weight of sand the same height. Time, therefore, is not a factor which enters into the determination of work. In a minute, however, the man accomplished three times as much work as the boy. We say, therefore, that the man worked at three times the *rate*, or *speed*, of the boy. *The rate of doing work is called power.* Thus, if P represents power, W the work done, and t the time required to do the work, then

$$P = \frac{W}{t}, \quad \text{or} \quad P = \frac{Fs}{t}. \tag{10}$$

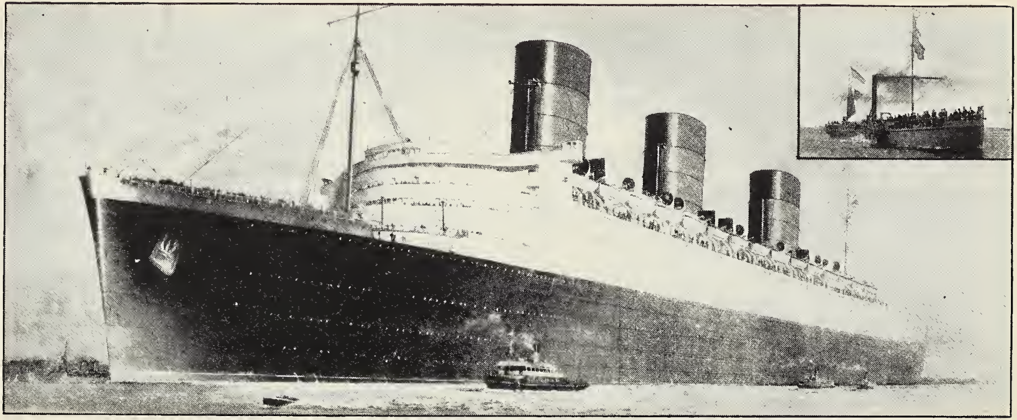
Horsepower. Since the first steam engines in England replaced horses in pumping water from the coal mines, it was only natural that their power should be compared with that of the horse. James Watt (1736–1819), one of the inventors of the steam engine, in a series of experiments estimated that an average horse could do 33,000 foot-pounds of work



The Rocket *and the Virginian* Mallet

This picture shows the relative sizes of Stephenson's original locomotive, the *Rocket*, which ran in October, 1829, between Manchester and Liverpool, and the most powerful locomotive thus far built, the Virginian *Mallet*, constructed in the shops of the American Locomotive Company at Schenectady, New York, for use on the Virginian Railroad.

The *Rocket* weighed $4\frac{1}{4}$ tons and won a prize of £500 by drawing a coach containing thirty people at a rate of from 26 to 30 miles per hour. The monster Virginian *Mallet* weighs 450 tons and is able to exert the enormous drawbar pull of 176,600 pounds. It develops approximately 5100 horsepower applied to ten driving wheels on each side



The Clermont *and the* Queen Mary

On August 22, 1787, the American John Fitch launched and successfully operated the first steamboat in the presence of the framers of the Constitution, then in session at Philadelphia. On July 26, 1788, he launched his second steamboat, a stern-wheeler, and in 1790 established and maintained for months scheduled sailings on the Delaware. In 1796 he constructed still another, using a screw propeller. In 1807, with the building of the *Clermont* by Fulton, steamship travel began to be popular. The progress made since then in this mode of application of steam power is illustrated above. The *Clermont* was 150 feet long and 13 feet wide, with a displacement of 100 tons and an average speed of 5 miles per hour. The *Queen Mary*, the biggest ship thus far built, is 1018 feet long and 118 feet wide, has a displacement of 80,773 tons and 20 acres of deck space, carries 2100 passengers and 1400 officers and crew. The four separate propellers have a combined horsepower of 200,000. (Courtesy of the Cunard White Star Line)

per minute, or 550 foot-pounds per second. The metric equivalent is 76.05 kilogram-meters per second. This number is probably considerably too high; but it has been taken ever since, in English-speaking countries, as the unit of power, and named the *horsepower* (H.P.). The power of steam engines has usually been rated in horsepower. The horsepower of an ordinary railroad locomotive is from 500 to 1000. Stationary engines and steamboat engines of the largest size often run from 5000 to 45,000 horsepower. The power of an average horse is about $\frac{3}{4}$ horsepower, and that of a man about $\frac{1}{7}$ horsepower. It is important to note, however, that for a short period of time, such as that required to run upstairs, a man may work at a greater rate than that of 1 horsepower. A horsepower-hour is a unit of work, not of power.

The kilowatt. In the metric system the erg is taken as the absolute unit of work. The corresponding unit of power is an erg per second. This is, however, so small that it is customary to take as the practical unit 10,000,000 (10^7) ergs per second; that is, one joule per second. (See page 150.) This unit is called the *watt*, in honor of James Watt. The power of dynamos and motors is almost always expressed in kilowatts, a kilowatt being 1000 watts; and in modern practice even steam engines are being increasingly rated in kilowatts rather than in horsepower. A horsepower is 746 watts, or about $\frac{3}{4}$ of a kilowatt. A kilowatt-hour is a much used unit of *work*.

Definition of energy. Energy is defined as the capacity for doing work. Many objects possess energy only because of work which has been done on them at some previous time. Thus suppose a kilogram weight is lifted from position 1 in Fig. 156 through a height of 1 meter and placed upon the hook H at the end of a cord passing over a frictionless pulley p and attached at the other end to a second kilogram weight. To lift A from position 1 to position 2 has required 1 kilogram-meter

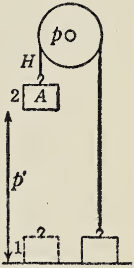


FIG. 156. Illustration of potential energy

(100,000 gram-centimeters, or 98,000,000 ergs) of work. But in position 2 the weight *A* itself has a certain capacity for doing work that it did not have before; for if it is now started downward with the slightest push, it will of its own accord return to position 1, and in so doing will raise the kilogram weight *B* through the height of 1 meter. In other words, it will do upon *B* exactly the same amount of work that was originally done upon it.

Potential and kinetic energy. A body may have a capacity for doing work not only because it has been given an elevated position but also because it has in some way acquired velocity; for example, a heavy flywheel will keep machinery running for some time after the power has been shut off, and a bullet shot upward will lift itself a great distance against gravity because of the velocity which has been imparted to it. Similarly any body which is in motion is able to rise against gravity or to set other bodies in motion by colliding with them or to overcome resistance. Hence, in order to distinguish between the energy that a body may have because of an *advantageous position* and the energy that it may have because it is in *motion*, the two terms *potential energy* and *kinetic energy* are used. Potential energy includes the energy of lifted weights, of coiled or stretched springs, of bent bows, etc.; in a word, *potential energy is energy of position, and kinetic energy is energy of motion.*

Transformations of potential and kinetic energy. The swinging of a pendulum and the oscillation of a weight attached to a spring illustrate very well the way in which energy that has once been put into a body may be changed back and forth between the potential and kinetic varieties. When the pendulum bob is at rest at the bottom of its arc it has no energy of either type, since, on the one hand, it is as low as it can be, and, on the other, it has no velocity. When we pull it up the arc to the position *A* (Fig. 157), we do upon it an amount of work equal in gram-centimeters to its weight in grams times the distance *AD* in centimeters; that is, we store up in it this amount of potential energy. As the bob

falls to C, this potential energy is completely transformed into kinetic energy. That this kinetic energy at C is exactly equal to the potential energy at A is proved by the fact that, if friction is completely eliminated, the bob rises to a point B such that BE is equal to AD. We see, therefore, that at the ends of its swing the energy of the pendulum is all potential, whereas in the middle of the swing its energy is all kinetic. In positions in between, the energy is part potential and part kinetic, but *the sum of the two is equal to the original potential energy.*

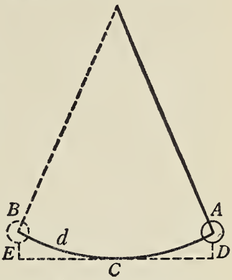


FIG. 157. Transformation of potential and kinetic energy

Let a small weight be attached to a long, delicate spiral spring (Fig. 158). If energy is expended to lift the weight from position 1 to position 2, potential energy is conferred upon it. When the hand is suddenly removed, the weight slowly falls, and at 3 the energy is all in the kinetic form. As the weight passes to 4, its kinetic energy is transformed into potential energy in the stretched spring, which then lifts the weight to 5, where the energy is again all in the kinetic form. The kinetic energy in the weight at 5 does the work of lifting it to 6, where the energy is once more all potential, as at 2.

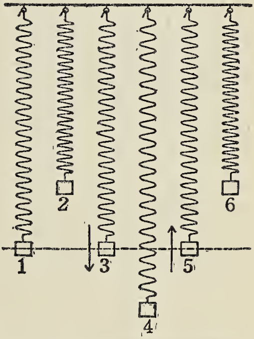


FIG. 158. Transformation of potential and kinetic energy

Opposite page 123 is shown a pile-driver, used for pounding big timber into the earth. An engine lifts a very heavy weight to various heights, from which it descends as a freely falling body to do its work. It is kept in a straight course by guides.

General statement of the law of frictionless machines. In our development of the law of machines, which led us to the conclusion that the work of the acting force is always equal to the work of the resisting force, we were careful to make two important assumptions: first, that friction was negligible; secondly, that the motions were all either uniform or so slow that no appreciable velocities were imparted. In other words, we assumed that the work of the acting force was expended simply in lifting weights or in compressing springs, that is, in storing up potential energy. If we drop the second assumption, a very simple experiment will serve to show that our conclusion must be somewhat modified. Suppose, for instance, that instead of lifting a 500-gram weight slowly by means of a balance, we jerk it up suddenly. We shall now find that the initial pull indicated by the balance, instead of being 500 grams, will be considerably more — perhaps as much as several thousand grams if the pull is sufficiently sudden. This is obviously because the acting force is now overcoming not merely the 500 grams which represents the resistance of gravity, but also the inertia of the body, since velocity is being imparted to it. Now work done in imparting velocity to a body (that is, in overcoming its inertia) always appears as *kinetic* energy; work done in overcoming gravity appears as the *potential* energy of a lifted weight. Hence, whether the motions produced by machines are slow or fast, if friction is negligible the law for all devices for transforming work may be stated thus: *The work of the acting force is equal to the sum of the potential and kinetic energies stored up in the mass acted upon.* In machines which work against gravity the body usually starts from rest and is left at rest, so that the kinetic energy resulting from the whole operation is zero. Hence in such cases the work done is the weight lifted times the height through which it is lifted, whether the motion is slow or fast. The kinetic energy imparted to the body in starting is all given up by it in stopping. Analyze the case of a loaded sled, started, moved uniformly, and stopped on frictionless ice.

The measure of potential energy. The measure of the potential energy of any lifted body, such as a lifted pile-driver, is equal to the work which has been spent in lifting the body. Thus if h is the height in centimeters and W the weight in grams, then the potential energy (P.E.) of the lifted mass is

$$\text{P.E.} = Wh \text{ g-cm.} \tag{11}$$

Similarly, if h is the height in feet and W the weight in pounds,

$$\text{P.E.} = Wh \text{ ft-lb.}$$

The measure of kinetic energy. Since the force of the earth's attraction for M grams is Mg dynes, if we wish to express the potential energy in ergs instead of in gram-centimeters we have

$$\text{P.E.} = Mgh \text{ ergs.} \tag{12}$$

Since this energy is all transformed into kinetic energy when the mass falls the distance h, the product Mgh also represents the number of ergs of kinetic energy which the moving weight has when it strikes the pile.

If we wish to express this kinetic energy in terms of the velocity with which the weight strikes the pile, instead of the height from which it has fallen, we have only to substitute for h its value in terms of g and the velocity acquired (see equation (7), p. 114); namely, $h = v^2/2\,g$. This gives the kinetic energy (K.E.) in the form

$$\text{K.E.} = \tfrac{1}{2} Mv^2 \text{ ergs.} \tag{13}$$

Since it makes no difference how a body has acquired its velocity, this represents the general formula for the kinetic energy *in ergs* of any moving body, in terms of its mass and its velocity.

Thus the kinetic energy of a 100-gram bullet moving with a velocity of 10,000 centimeters per second is

$$\text{K.E.} = \tfrac{1}{2} \times 100 \times (10{,}000)^2 = 5{,}000{,}000{,}000 \text{ ergs.}$$

Since 1 gram-centimeter is equivalent to 980 ergs, the energy of this bullet is $5{,}000{,}000{,}000/980 = 5{,}102{,}000$ gram-centimeters, or 51.02 kilogram-meters.

We know, therefore, that the powder pushing on the bullet as it moved through the rifle barrel did 51.02 kilogram-meters of work upon the bullet in giving it the velocity of 100 meters per second.

In general terms, if M is in grams and v in centimeters per second, K.E. $= \frac{1}{2}Mv^2/980$ gram-centimeters; if M is in pounds and v in feet per second, K.E. $= \frac{1}{2}Mv^2/32.16$ foot-pounds.

Summary. Power is the rate of doing work; that is, $P = W/t$.

One horsepower = 33,000 foot-pounds per minute = 550 foot-pounds per second = 746 watts = $\frac{3}{4}$ kilowatt.

One watt = 10,000,000 ergs per second = 1 joule per second.

The energy of a body is its capacity for doing work. Kinetic energy is energy of motion; potential energy is energy of position.

***General law of ideal frictionless machines when velocity is being imparted to mass.* The work of the acting force is equal to the sum of the potential and kinetic energies stored up in the mass acted upon.**

The potential energy of an uplifted weight equals its weight times its height; that is, P.E. = Wh gravitational units = Mgh absolute units.

The kinetic energy of a moving mass equals $\frac{1}{2}Mv^2$ absolute units, or $\frac{1}{2}Mv^2/g$ gravitational units.

QUESTIONS AND PROBLEMS

A

1. A boy weighing 100 lb runs up a flight of stairs 10 ft high in 5 sec. What is his horsepower during this time?

2. (*a*) If the speed of an automobile is tripled, what change will there be in its kinetic energy? (*b*) Compare the damage done at each speed in case of a collision. (See equation (13) above.)

3. An electric motor hoisted a block of granite weighing 6600 lb 100 ft in 2 min. (*a*) At what power (expressed as foot-pounds per minute) was work done on the block of granite? (*b*) What is this rate expressed as horsepower?

4. What horsepower is needed to draw a load of 5 t at a uniform rate up a hill 50 ft high in 10 min?

5. What horsepower is required to run an automobile on a level road at the rate of 30 mi/hr if the forces of friction amount to 125 lb?

6. A farm tractor drew a gang plow at the rate of $2\frac{1}{2}$ mi/hr, maintaining an average drawbar pull of 1500 lb. At what average horsepower was the tractor working?

B

1. (*a*) If engine speed remains constant, does an automobile have more power in low gear than it has in high gear? In practice what happens to (*b*) engine speed, (*c*) engine horsepower, and (*d*) useful power when we shift to low gear?

2. Why is it that one horse may pull an automobile out of the mud when its 100-horsepower engine is unable to move it?

3. A stick of dynamite has great capacity for doing work. Before the explosion occurs, is the energy in the potential form or in the kinetic form?

4. Explain the use of the sandblast in cleaning castings, making frosted glass, cutting figures on glassware, cleaning off the walls of stone buildings, etc.

5. (*a*) How much work is required to lift the 500-pound weight of a pile-driver 30 ft? (*b*) How much potential energy is then stored in it? (*c*) How much work does it do when it falls? (*d*) If the falling mass drives the pile into the earth $\frac{1}{2}$ ft, what is its average force upon the pile? (See opposite page 123.)

6. In the course of a stream there is a waterfall 22 ft high. It is shown by measurement that 450 ft^3 of water per second pours over it. (*a*) What power in foot-pounds of energy per second could be obtained from it? (*b*) What horsepower?

7. If a rifle weighing 5 kg fired a bullet weighing 10 g with a velocity of 700 m/sec, what was the velocity of recoil of the rifle? (Use Newton's third law.)

8. Show that the energy of the bullet exceeds that of the rifle.

9. A man weighing 198 lb walked up the stairway of the Washington Monument (500 ft high) in 10 min. (*a*) At what power did he work in foot-pounds per minute? (*b*) At what horsepower? (*c*) If he had gone up in 20 min, what would have been the power?

10. A cannon ball is moving at a height of 4 mi with a speed of 1600 ft/sec. If the weight of the projectile is 1000 lb, (*a*) how much kinetic energy has it? (*b*) how much potential energy? (Calculate your results in foot-pounds.)

11. A 2000-barrel water tank at 40 ft mean elevation is to be filled with water. (*a*) Assume that a barrel of water weighs 260 lb; how much work is required to fill the tank? (*b*) If the work is done by a motor-driven pump working at the rate of 4 H.P., how many minutes are required to fill the tank?

12. What is the force of the backward thrust of the propeller of an airplane driven by an engine developing 150 H.P. when the airplane is traveling 120 mi/hr?

Friction

Friction always results in wasted work. When we slide a block across the floor, it soon comes to rest. Some force must therefore have acted upon it. The resistance which opposes every effort to slide or roll or in any other way move one body at constant speed over or through another is called friction. All the experiments mentioned in this chapter have been so arranged that *friction* could be neglected or eliminated. So long as this was true, experience has shown us that *the work done by the acting force is equal to the sum of the kinetic and potential energies stored up* (p. 174).

But wherever friction is present, this law is found to be inexact; for the work of the acting force is then always somewhat greater than the sum of the kinetic and potential energies stored up. If, for example, a block is pulled over the horizontal surface of a table, at the end of the motion no velocity has been imparted to the block, and hence no kinetic energy has been stored up. Furthermore, the block has not been lifted nor put into a condition of elastic strain, and hence no potential energy has been given it. We cannot in any way obtain from the block more work after the motion than we could have obtained before it was moved. It is clear, therefore, that all the work which was done in moving the block against the friction of the table was *wasted work.* Experience shows that, in general, where work is done against friction it can never be regained. Before considering what becomes of this wasted work we will consider some of the factors on which friction depends.

The coefficient of friction. Friction between solids is mainly due to the inequalities which occur on the surfaces of the two bodies which are in contact (Fig. 159). If we magnify these surfaces, no matter how hard or polished they may be, we shall see hills and hollows which tend to catch on one another. Sliding friction may be lessened by filling in these hollows with some lubricant, such as oil, grease, or graphite.

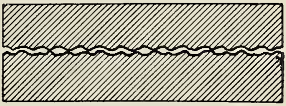


FIG. 159. Friction is caused by irregular surfaces

If the two surfaces are of the same material, the irregularities will probably fit into one another more closely than if different substances are used, and the friction will thus be greater. Machines with steel axles often have bearings of bronze or Babbitt metal (an alloy of antimony, tin, and copper).

Sliding friction is mainly independent of speed, although starting friction is somewhat greater than friction when in motion. Likewise a motorman eases off his brakes as the car comes to a stop because the hills and hollows tend to drop into one another at the lower speeds and thus tend to cause a greater stopping effect.

The amount of friction does not depend to any extent on the area of the surfaces in contact. Thus a spring balance attached to a brick shows about the same pull, regardless of whether the brick is pulled flat, on its side, or on an end.

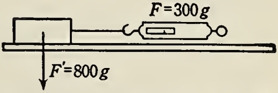


FIG. 160. The ratio of F to F' is the coefficient of friction

Fig. 160 illustrates a method of comparing the frictional properties of various surfaces and materials so that the best combination may be chosen for each condition of use. The ratio $\frac{F}{F'}$ is called the coefficient of friction of the given materials. In this case the coefficient is $\frac{300}{800} = .375$.

Rolling friction. To drag a heavy barrel across a floor would require a very large force, but it may be easily rolled along. Rolling friction is, then, very much less than sliding friction.

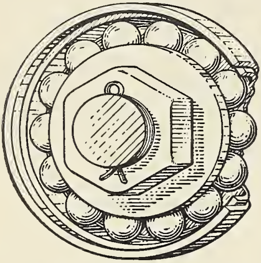


FIG. 161. Ball bearing

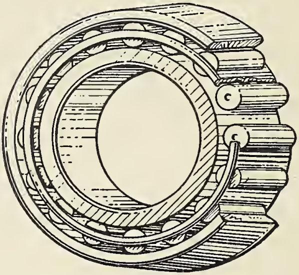


FIG. 162. Roller bearing

For example, the coefficient of friction of iron wheels rolling on iron rails may be as low as .002, that is, $\frac{1}{100}$ that of the sliding friction of iron on iron. This means that a pull of 1 pound will keep a 500-pound car in motion.

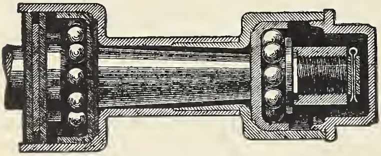


FIG. 163. The bicycle pedal

Ball bearings (Figs. 161 and 163) and roller bearings (Fig. 162), as used in bicycles and automobiles, illustrate the very great advantages of rolling friction over sliding friction. Equipping our best trains of today with roller bearings has increased the load that can be drawn by the engine and likewise the comfort of the passengers riding on the train.

Advantages of solid friction. While friction is usually considered as something to be avoided as much as possible, it must be remembered that there are many circumstances in which it plays a very important and necessary part. If there were no friction, we could not walk about, automobiles could

not run, and nails and screws could not be used to hold wood together. Automobiles driven at high speeds are stopped quickly and smoothly by the friction between the brake lining and the brake drum, and power is transmitted to the rear wheels by means of the friction clutch.

Friction of fluids. When a solid moves through a fluid, as when a bullet moves through the air or a ship moves through the water, the resistance encountered is not at all independent of velocity, as in the case of solid friction, but increases for slow speeds nearly as the square of the velocity and for high speeds at a rate considerably greater. This explains why it is so expensive to run a fast train; for the resistance of the air, which is a small part of the total resistance so long as the train is moving slowly, becomes the important factor at high speeds.

The increasing automobile speeds of today are causing the designers to pay attention to the problem of properly *streamlining* car bodies to minimize wind resistance, although this does not become an important factor until speeds of over 40 miles per hour are reached.

The resistance offered to steamboats running at high speeds is usually considered to increase as the cube of the velocity. Thus the *Cedric*, of the old White Star Line, having a speed of 17 knots, had a horsepower of 14,000 and a total weight when loaded of about 38,000 tons; whereas the *Mauretania*, of the old Cunard Line, having a speed of 25 knots, had engines of 70,000 horsepower, although the total weight when loaded was only 32,500 tons.

Summary. **Work done against friction is entirely wasted.**

Friction changes little with velocity or with area of surface in contact.

Friction may be made less by proper choice of materials, by lubricating, or by substituting rolling friction for sliding friction.

The coefficient of friction is the ratio of the force required to overcome friction to the perpendicular force pressing the two surfaces together.

Friction plays a necessary part in many of our activities.

QUESTIONS AND PROBLEMS

A

1. Why do we not get out of a machine all the work we put into it?

2. (*a*) Define friction. (*b*) What causes it?

3. Why is sand often placed on a track in starting a heavy train?

4. (*a*) In what way is friction an advantage in lifting buildings with a jackscrew? (*b*) In what way is it a disadvantage?

5. Why is a stream swifter at the center than at the banks?

6. Why does a team have to keep pulling after a load is started?

7. (*a*) In what respects is friction an advantage in everyday life? (*b*) In what respects is it a disadvantage? (*c*) Could we get along without it?

8. Mention three ways of lessening friction in machinery.

9. What is the coefficient of friction of brass on brass if a force of 25 lb is required to maintain uniform motion in a brass block weighing 200 lb when it slides horizontally on a brass bed?

B

1. The coefficient of friction between a block and a table is 0.3. What force will be required to keep a 500-gram block in uniform motion?

2. What horsepower must be used to pull a body weighing 5 t along a horizontal surface at the rate of 6 mi/hr, the coefficient of friction being 0.2?

3. A smooth block is $10 \times 8 \times 3$ in. Compare the distances which it will slide when given a certain initial velocity on smooth ice if resting (*a*) on a 10×8 face; (*b*) on a 10×3 face; (*c*) on an 8×3 face.

Efficiency

Definition of efficiency. In every machine some energy must be supplied to overcome friction. In a system of pulleys, such as the block and tackle, energy is wasted in overcoming the friction of the pulley bearings, in bending the ropes around the pulleys, and in lifting the movable pulley

itself. In all actual machines the work done by the acting force always exceeds, by the amount of the work done against friction, the amount of potential and kinetic energy stored up. This work done against friction is wasted work in the sense that it can never be regained. Any energy stored up represents work that can be regained, and such work is called useful work. In practice we are more interested in what a machine actually does than in what it should do. *The ratio of the useful work to the total work done by the acting force is called the* EFFICIENCY *of the machine.* Thus

$$\text{Efficiency} = \frac{\text{useful work accomplished}}{\text{total work expended}}, \text{ or } \frac{\text{output}}{\text{input}}. \quad (14)$$

Thus, if in the system of pulleys shown in Fig. 130 it is necessary to add a weight of 50 grams at E in order to pull up slowly an added weight of 240 grams at R, the work done by the 50 grams while E is moving over 1 centimeter will be $50 \times 1 = 50$ gram-centimeters. The useful work accomplished in the same time is $240 \times \frac{1}{6} = 40$ gram-centimeters. Hence the efficiency is equal to

$$\frac{240 \times \frac{1}{6}}{50 \times 1} = \frac{40}{50} = 80 \text{ per cent.}$$

Students often confuse the ideas of efficiency and mechanical advantage. Efficiency is concerned with *work*, and is the relation between the work accomplished by a machine and the work applied to it. On the other hand, mechanical advantage deals with *forces*, and is the relation between the force exerted by a machine and the force applied to it.

Efficiencies of some simple machines. In simple levers the friction is generally so small as to be negligible; hence the efficiency of such machines is approximately 100 per cent. When inclined planes are used as machines the friction is also small, so that the efficiency generally lies between 90 per cent and 100 per cent. The efficiency of the commercial block and tackle (Fig. 130), with several movable pulleys, is usually considerably less, varying between 40 per cent and 60 per

cent. In the jackscrew there is necessarily a very large amount of friction, so that although the mechanical advantage is enormous, the efficiency is often as low as 25 per cent. The differential pulley of Fig. 154 has also a very high mechanical advantage with a very small efficiency. Gear wheels, such as those shown in Fig. 152, or chain gears, such as those used in bicycles, are machines of comparatively high efficiency, often utilizing between 90 per cent and 100 per cent of the energy expended upon them.

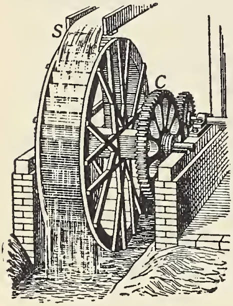


FIG. 164. Overshot water wheel

Efficiency of overshot water wheels. The overshot water wheel (Fig. 164) utilizes chiefly the potential energy of the water at S, for the wheel is turned by the weight of the water in the buckets. The work expended on the wheel per second, in foot-pounds or in gram-centimeters, is the product of the weight of the water which passes over it per second and the distance through which it falls. The efficiency is the work which the wheel can accomplish in a second divided by this quantity. Such wheels are very common in mountainous regions, where it is easy to obtain considerable fall but where the streams carry a small *volume* of water. The efficiency is high, being often between 80 per cent and 90 per cent. The loss is due not only to the friction in the bearings and gears (see C) but also to the fact that some of the water is spilled from the buckets or passes over without entering them at all. This may still be regarded as a frictional loss, since the energy disappears in internal friction when the water strikes the ground.

Efficiency of undershot water wheels. The old-style undershot wheel (Fig. 165), so common in flat countries where there is little fall but an abundance of water, utilizes only the kinetic energy of the water running through the race from A. It seldom transforms into useful work more than 25 per cent

or 30 per cent of the potential energy of the water above the dam. There are, however, certain modern forms of undershot wheel which are extremely efficient. For example, the *Pelton wheel* (Fig. 166), developed since 1880 and used for operating huge power plants, sometimes has an efficiency as high as 87 per cent. The water is delivered from a nozzle *O* against cup-shaped buckets arranged as in the figure. At the Big Creek development in California, Pelton wheels 121 inches in diameter are driven by water coming with a velocity of 350 feet per second (how many miles per hour?) through nozzles 6 inches in diameter. The head of water (drop) is here 2130 feet. (See opposite page 187.)

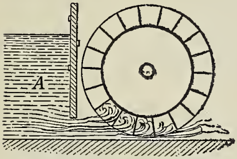


FIG. 165. The undershot wheel

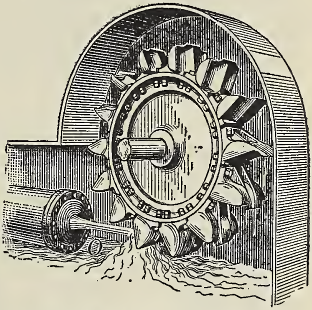


FIG. 166. The Pelton water wheel

Efficiency of water turbines. The turbine wheel was invented in France in 1833 and is now used more than any other form of water wheel. It stands completely under water in a case at the bottom of a *turbine pit* and rotates in a horizontal plane. Fig. 167 (*a*) shows one form of outer case with contained turbine; Fig. 167 (*b*) is the inner case, in which are the fixed guides *G*, which direct the water at the most advantageous angle against the blades of the wheel inside; Fig. 167 (*c*) is the wheel itself; and Fig. 167 (*d*) is a section of wheel and inner case, showing how the water enters through the guides and strikes the blades *W*. The spent water simply falls down from the blades into the tailrace below *T* (Fig. 167 (*a*)). The amount of water which passes

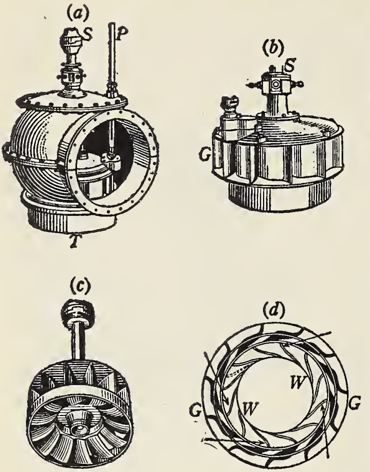


FIG. 167. The turbine wheel: (*a*) outer case; (*b*) inner case; (*c*) rotating part; (*d*) section

through the turbine can be controlled by means of a valve *P* (Fig. 167 (*a*)), which can be turned so as to increase or decrease the size of the openings between the guides *G* (Fig. 167 (*b*)). Opposite this page is shown a huge modern turbine installation. The energy expended upon the turbine per second is the product of the weight of water which passes through it by the height of the turbine pit. Efficiencies as high as 93 per cent have been attained with such wheels.

Summary. **The efficiency of a machine is the ratio of its useful output of work to the total input of work (work done on the machine); that is,**

$$\textbf{Efficiency} = \frac{\textbf{output}}{\textbf{input}}.$$

The efficiency of the simple machines varies greatly: in the case of a simple lever it may be almost 100 per cent and in the jackscrew as low as 25 per cent.

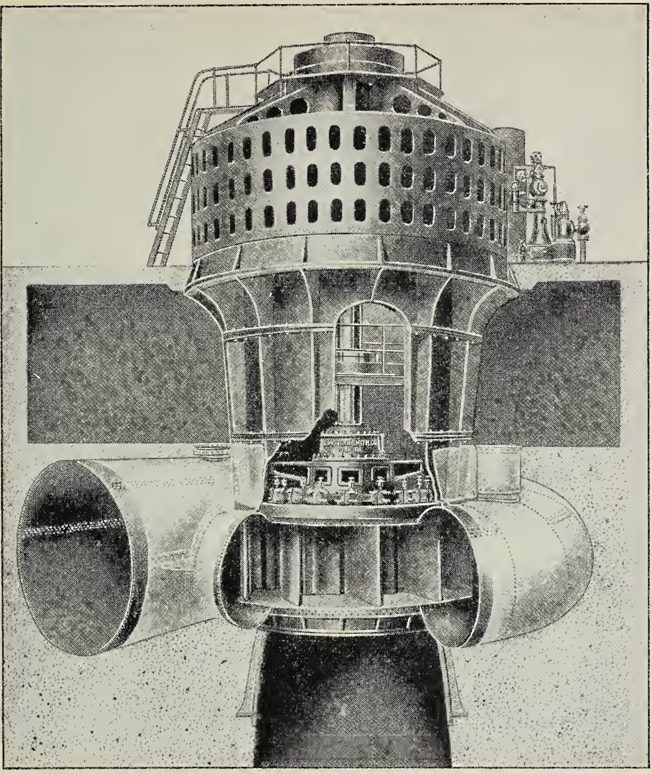
QUESTIONS AND PROBLEMS

A

1. (*a*) Distinguish between the mechanical advantage of a machine and its efficiency. (*b*) How is each calculated?

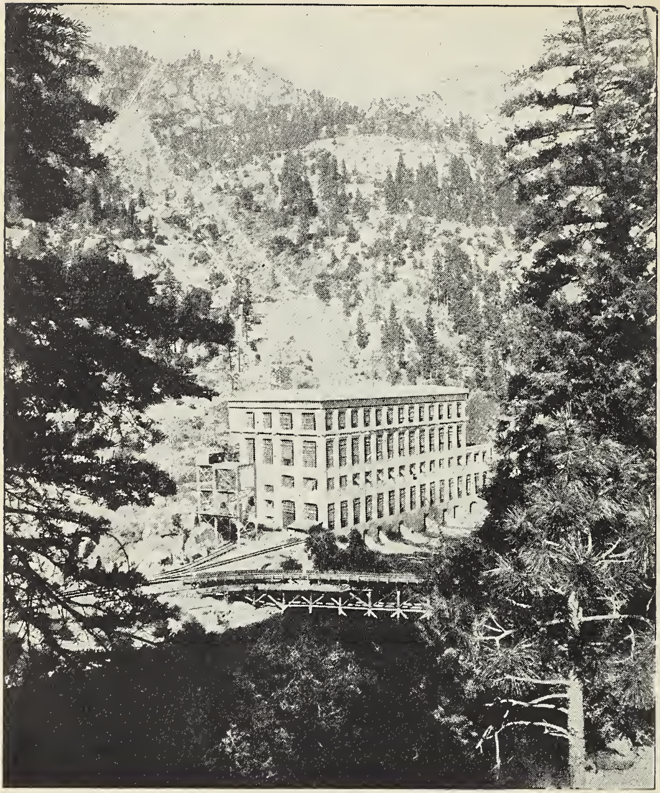
2. Why is the efficiency of the jackscrew low and that of the lever high?

3. Find the efficiency of a machine in which an effort of 12 lb moving 5 ft raises a weight of 25 lb a distance of 2 ft.



A Turbogenerator

On the American side of the Niagara River are installed three turbines, similar to the one shown in the picture, of 70,000 horsepower, each operating under a head of 213.5 feet. They are the highest-powered turbines in the world. The picture shows clearly how the water enters a volute casing surrounding the whole wheel, from which it is evenly distributed against the blades of the huge runner 15 feet in diameter. Each of these complete turbines, not including the generators above, weighs 1,250,000 pounds, makes 107 revolutions per minute, and has an efficiency of 93 per cent. The generator shaft is of solid steel 34 inches in diameter. (Courtesy of the Westinghouse Electric and Manufacturing Company)



A Hydroelectric Plant in the High Sierras

This is one of the Southern California Edison Company's hydroelectric power plants. Large water storage at an elevation of 7000 feet is obtained by two huge dams and a 13-mile-long tunnel through granite rock. The vertical drop of this water through more than a mile is fully utilized by a series of power plants. The picture shows one of these, in which are installed Pelton wheels fed from a penstock 4333 feet long (seen on the mountain side) and having a vertical drop of 2130 feet. Each of these Pelton wheels has a maximum output of 43,000 horsepower and an efficiency of 88 per cent. The power is transmitted 241 miles at 220,000 volts

4. Compute the efficiency of a machine which is run by a 2-horsepower motor if the machine can do but 50,000 ft-lb of work per minute.

5. A man weighing 150 lb carries a bag of corn weighing 100 lb up three flights of stairs, a total height of 25 ft. (*a*) How much work is done? (*b*) How much *useful* work is done? (Is any useful work done by the man's moving himself upstairs?) (*c*) What is his efficiency? (*d*) How could he use a simple machine to do his work with greater efficiency?

B

1. An electric motor the energy input of which is 40 kw will supply 40 H. P. What is its efficiency?

2. A steam shovel driven by a 5-horsepower engine lifts 200 t of gravel to a height of 15 ft in an hour. (*a*) What is the efficiency of the steam shovel? (*b*) What percentage of the power is lost because of friction?

3. (*a*) At what average horsepower does a man work who loads 30 bricks a minute from the ground to a wagon 4 ft from the ground? Each brick weighs 7 lb. (*b*) What is his efficiency if he tosses them 1 ft higher than necessary?

4. What amount of work was done on a block and tackle having an efficiency of 60 per cent when by means of it a weight of 750 lb was raised 50 ft?

5. Turbines at Niagara have a horsepower of 70,000 and an efficiency of 93 per cent. The head of water is 213.5 ft. How many cubic feet of water does each turbine discharge per minute?

6. If it is necessary to pull on a block and tackle with a force of 100 lb in order to lift a weight of 300 lb, and if the force must move 6 ft to raise the weight 1 ft, what is the efficiency of the system?

7. Over a waterfall 22 ft high flows 450 ft^3 of water each second. What horsepower could be developed if all the water were utilized by a water wheel having an efficiency of 80 per cent?

CHAPTER VIII

Thermometry; Expansion Coefficients*

Thermometry

Meaning of temperature. When a body feels hot to the touch, we are accustomed to say that it has a *high temperature*; when it feels cold, we say that it has a *low temperature.* Thus the word *temperature* is used to denote the condition of hotness or coldness of the body whose state is being described.

Measurement of temperature. So far as we know, up to the time of Galileo no one had ever used any special instrument for the measurement of temperature. People knew how hot or how cold it was from their feelings only. But under some conditions this sense of temperature is a very unreliable guide. On a winter day metals feel colder than wood, even though they have the same temperature. Likewise, if the hand has been in hot water, lukewarm water will feel cold; if it has been in cold water, the same lukewarm water will feel warm; a room may feel warm to one who has been running, whereas it will feel cool to one who has been sitting still.

Difficulties of this sort have led to the introduction in modern times of mechanical devices called *thermometers,* for measuring temperature. These instruments depend for their operation upon the fact that almost all bodies expand as they grow hot.

Galileo's thermometer. It was in 1592 that Galileo, at the University of Padua, constructed the first thermometer.

* It is recommended that this chapter be preceded by laboratory measurements on the expansions of a gas and solid. See, for example, Experiments 20 and 21 of *Exercises in Laboratory Physics,* by Millikan, Gale, and Davis.

He was familiar with the facts of expansion of solids, liquids, and gases; and since gases expand more than solids or liquids, he chose a gas as his expanding substance. His device was that shown in Fig. 168.

Connect a bulb of air *B* with a glass tube containing some water, and immerse the end of the tube in a dish of water (Fig. 168). If the bulb is warmed by placing the hand on it, the water at *m* will at once begin to descend, showing that the pressure exerted by the air contained in the bulb has been increased by the increase in its temperature. If *B* is cooled with ice or ether, the water will rise at *m*.

FIG. 168. Expansion of air by heat

Meaning of temperature from the standpoint of the kinetic theory. If, as was stated on page 75, gas pressure is due to the bombardment of the walls by the molecules of the gas, then, since the number of molecules in the bulb can scarcely have been changed by slightly heating it, we are forced to conclude that the increase in pressure is caused by an increase in the *velocity* of the molecules which are already there. From the standpoint of the kinetic theory (see Chapter IV) the pressure exerted by a given number of molecules of a gas is determined by the kinetic energy of bombardment of these molecules against the containing walls. To increase the temperature is to increase the average kinetic energy of the molecules; to diminish the temperature is to diminish this average kinetic energy. In simpler terms, when a body is warmed, its molecules move more rapidly; conversely, when it is cooled, they move less rapidly. If the volume of the containing vessel is kept the same, this increased motion shows merely as an increased pressure on the walls; on the other hand, if the gas is in a cylinder and is free to expand upward against a piston, the pressure will remain the same, and the volume becomes larger. The kinetic theory thus furnishes a very simple and natural explanation of the fact of the expansion of gases with a rise in temperature.

Construction of a centigrade mercury thermometer. Galileo's air thermometer was a very sensitive one, but it was unreliable, owing to the fact that its reading changed with the air pressure outside as well as with the temperature. Forty years later Jean Rey, a Frenchman, made water instead of air the thermometric substance by inverting Galileo's thermometer and filling the bulb and part of the stem with this liquid. Thermometer tubes were not sealed at the top until a quarter of a century later. It was not until about 1700 that mercury thermometers were invented.

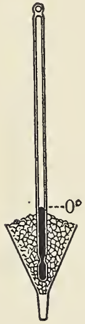


FIG. 169. Method of finding the 0° point in calibrating a thermometer

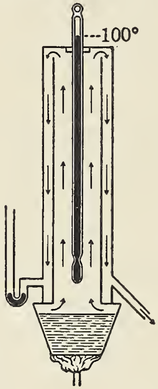


FIG. 170. Method of finding the 100° point in calibrating a thermometer

The meaning of a degree of temperature change as measured by a mercury thermometer is best understood from a description of the method of making and graduating the thermometer.

A bulb is blown at one end of a piece of thick-walled glass tubing of small, uniform bore. Bulb and tube are filled with mercury at a temperature slightly above the highest temperature for which the thermometer is to be used, and the tube is sealed off in a hot flame. As the mercury cools, it contracts and falls away from the top of the tube, leaving a vacuum above it.

The bulb is next surrounded with melting snow or ice, as in Fig. 169, and the point at which the mercury stands in the tube is marked 0°. Then the bulb and tube are placed in the steam rising from boiling water under a pressure of 76 centimeters, as in Fig. 170, and the new position of the mercury is marked 100°. The space between these two

marks on the stem is then divided into 100 equal parts, and divisions of the same length are extended above the 100° mark and below the 0° mark.

Therefore *one degree* of change in temperature, measured on such a thermometer, means such a temperature change as will cause the mercury in the stem to move over one of these divisions; that is, it is such a temperature change as will cause the mercury contained in a glass bulb to expand $\frac{1}{100}$ of the amount which it expands in passing from the temperature of melting ice to that of steam under a pressure of 76 centimeters. A thermometer in which the scale is divided in this way is called a centigrade thermometer.

Thermometers graduated on the centigrade scale are used almost exclusively in scientific work, and also for ordinary purposes in most countries which have adopted the metric system. This scale was first devised in 1742 by Celsius, of Uppsala, Sweden. For this reason it is sometimes called the Celsius scale instead of the centigrade.

According to the kinetic theory an increase in temperature in a liquid, as in a gas, means an increase in the mean kinetic energy of the molecules; conversely a decrease in temperature means a decrease in this average kinetic energy.

Fahrenheit thermometers. The common household thermometer in England and the United States differs from the centigrade only in the way in which it is marked off, or graduated. In its construction the temperature of melting ice is marked 32° instead of 0°, and that of boiling water 212° instead of 100°. The space between these two points is then divided into 180 parts. The zero of this scale is the temperature obtained by mixing equal weights of sal ammoniac (ammonium chloride) and snow. In 1714, when Fahrenheit devised this scale, he chose this zero because he thought it represented the lowest possible temperature that could be obtained in the laboratory.

Comparison of centigrade and Fahrenheit scales. It is frequently necessary for the student to change a temperature on one scale to the corresponding value on the other. It will

be seen that a change of 100° on the centigrade scale is the same difference of temperature as a change of 180° on the Fahrenheit scale (Fig. 171). Hence a temperature difference of five centigrade degrees is equal to nine Fahrenheit degrees. Likewise, since zero on the centigrade scale corresponds to 32° on the Fahrenheit scale, there must always exist this difference also between the two scales.

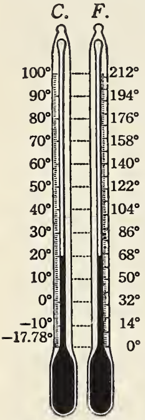


Fig. 171. Centigrade and Fahrenheit scales

Thus 68° F. is $68° - 32° = 36°$ above the same reference point on both scales, namely, the freezing point of water, and $36° \times \frac{5}{9} = 20°$ C. *Hence to change from F. to C. temperatures, subtract 32 and multiply by $\frac{5}{9}$; to change from C. to F. temperatures, reverse the process by multiplying by $\frac{9}{5}$ and adding 32.*

Range of the mercury thermometer. Since mercury freezes at $-39°$ C., temperatures lower than this are very often measured by means of *alcohol* thermometers, for the freezing point of alcohol is $-114°$ C. Similarly, since the boiling point of mercury is about 357° C., mercury thermometers cannot be used for measuring very high temperatures. For both very high and very low temperatures — in fact, for all temperatures — a *gas* thermometer is the standard instrument.

Fig. 172. Clinical thermometer

The fever thermometer. The human body in good health has the marvelous ability to maintain, summer and winter, indoors and out, a uniform temperature of 98.6° F. In time of sickness, however, this temperature may vary several degrees, and an accurate measuring device is of great value to the physician, nurse, and mother in the diagnosis and treatment of disease.

The fever, or clinical, thermometer (Fig. 172) is used for this purpose. It has a narrowing, or constriction, near the bottom of the stem. When the mercury is expanded by the heat of the body, it forces its way past the constriction. When the thermometer is removed, the mercury stays at its highest point until shaken down after the reading is taken. Its range is from 92° to 110° F.

The standard hydrogen thermometer. The modern gas thermometer (Fig. 173) is widely different from that devised by Galileo (Fig. 168). Such a thermometer generally measures temperatures not by the change in volume of the gas but by its change in pressure *when the volume is kept constant.* With this kind of thermometer *one degree of change in temperature on the centigrade scale is such a change as will cause the pressure exerted by the confined volume of hydrogen to change by $\frac{1}{273}$ of its pressure at the temperature of melting ice (0° C.).*

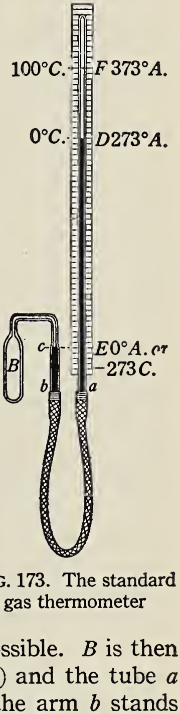


Fig. 173. The standard gas thermometer

If the foregoing definition is not quite clear from the figure alone, the following description of the method of calibration and use of the standard hydrogen thermometer at the International Bureau of Weights and Measures in Paris will make it so: First the bulb *B* (Fig. 173) is filled with hydrogen and the space above the mercury in the tube *a* is made as nearly a perfect vacuum as possible. *B* is then surrounded with melting ice (as in Fig. 169) and the tube *a* is raised or lowered until the mercury in the arm *b* stands exactly opposite the fixed mark *c* on the tube. Now, since the space above *D* is a vacuum, the pressure exerted by the hydrogen in *B* against the mercury surface at *c* just supports the mercury column *ED*. The point *D* is marked on a strip of

metal behind the tube *a*. The bulb *B* is then placed in a steam bath like that shown in Fig. 170. The increased pressure of the gas in *B* at once begins to force the mercury down at *c* and up at *D*. But by raising the arm *a* the mercury in *b* is forced back again to *c*, the increased pressure of the gas on the surface of the mercury at *c* being balanced by the increased height of the mercury column supported, which is now *EF* instead of *ED*. When the gas in *B* is thoroughly heated to the temperature of the steam, the arm *a* is very carefully adjusted so that the mercury in *b* stands very exactly at *c*, its original level. A second mark is then placed on the metal strip exactly opposite the new level of the mercury, that is, at *F*. Then *D* is marked 0° C., and *F* is marked 100° C. The vertical distance between these marks is divided into 100 exactly equal parts. Divisions of exactly the same length are carried above the 100° mark and below the 0° mark. One degree of change in temperature is then defined as any change in temperature which will cause the pressure of the gas in *B* to change by the amount represented by the distance between any two adjacent divisions. This distance is found to be $\frac{1}{273}$ of the height *ED*.

Absolute zero and absolute temperature. Since cooling the hydrogen through 1° C., as defined above, reduces the pressure $\frac{1}{273}$ of its value at 0° C., it is clear that cooling it 273° below 0° C. would reduce its pressure to zero. But from the standpoint of the kinetic theory this would be the temperature at which all motions of the hydrogen molecules would cease. This temperature is called the *absolute zero*, and the temperature measured from this zero is called *absolute temperature*. Thus, if A. is used to denote the absolute scale, we have 0° C. = 273° A., 100° C. = 373° A., 15° C. = 288° A., and so on. It is customary to indicate temperatures on the centigrade scale by t and on the absolute scale by T. We have, then,

$$T = t + 273. \tag{1}$$

Fig. 174 gives a comparison of the absolute scale with the Fahrenheit and centigrade scales.

The mercury thermometer yields temperatures which differ from the absolute scale by an amount that is negligible for ordinary purposes (less than 0.2° between 0° and 100°).

Low temperatures. The absolute zero of temperature can, of course, never be attained, but in recent years rapid strides have been made toward it. Fifty years ago the lowest temperature which had ever been measured was −110° C., the temperature attained by Faraday in 1845 by causing a mixture of ether and solid carbon dioxide to evaporate in a partial vacuum. But in 1880 air was first liquefied, and was found, by means of a gas thermometer, to have a temperature of −180° C. When liquid air evaporates into a space which is kept exhausted by means of an air pump, its temperature falls to about −220° C. Recently hydrogen has been liquefied and has been found to have a temperature at atmospheric pressure of −243° C. All these temperatures have been measured by means of hydrogen thermometers. By allowing liquid hydrogen to evaporate into a space kept exhausted by an air pump, Dewar in 1900 attained a temperature of −260°. In 1934 in Leiden, Holland, by the use of liquefied helium, a temperature of −272.7° C. was attained, and in 1935 the same experimenters reached a temperature less than 0.01° C. above absolute zero.

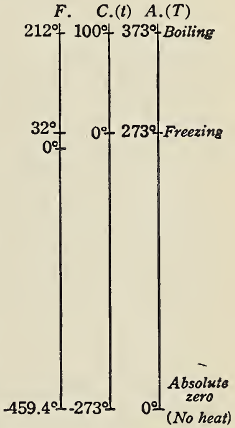


FIG. 174. Comparison of Fahrenheit, centigrade, and absolute scales

Summary. **The temperature of a body is the measure of the average kinetic energy of its molecules.**

Centigrade temperatures are changed to Fahrenheit by multiplying by $\frac{9}{5}$ and adding 32.

Fahrenheit temperatures are changed to centigrade by subtracting 32 and multiplying by $\frac{5}{9}$.

One degree centigrade is such a change in temperature as causes a body of hydrogen at constant volume to change its pressure by $\frac{1}{273}$ of the pressure that it exerts at the melting point of ice (0°C.).

The absolute zero is the temperature at which all motion of molecules would cease. It is 273° C. below the centigrade zero.

QUESTIONS AND PROBLEMS

A

1. Why is a fever thermometer made with a very long cylindrical bulb instead of a spherical one?

2. How does the distance between the 0° mark and the 100° mark vary with the cross-sectional area of the bore, the size of the bulb remaining the same?

3. Normal room temperature is 68° F. What is it centigrade?

4. What temperature centigrade corresponds to 0° F.?

5. Mercury freezes at about $-40°$ F. What is this centigrade?

6. Fudge is cooked until a Fahrenheit thermometer reads 236°. What would a centigrade thermometer read?

B

1. The temperature of liquid air is $-180°$ C. What is it Fahrenheit?

2. From a study of the behavior of gases we conclude that there is a temperature at which the molecules are at rest and at which bodies therefore contain no heat. Give the reasoning that leads to this conclusion.

3. What is meant by the absolute zero of temperature?

4. Is a platinum ball at 233° C. twice as hot as when it is 20° C. below zero? Give the reason for your answer.

5. What is the absolute zero of temperature on the Fahrenheit scale?

6. The normal temperature of the body is 98.6° F. What is it centigrade?

7. Two thermometers have bulbs of equal size. The bore of one has a diameter twice that of the other. What are the relative lengths of the stems between 0° and 100°?

Expansion Coefficients

The laws of Charles and Gay-Lussac. When, as in the experiment described on page 193, we keep the volume of a gas constant and observe the rate at which the pressure increases with the rise in temperature, we obtain *the pressure coefficient of expansion,* which is defined as *the ratio between the increase in pressure per degree and the value of the pressure at 0° C.* This was first done for different gases in 1787 by the French chemist Charles, who found that *the pressure coefficients of expansion of all gases are the same, namely,* $\frac{1}{273}$. This is known as *the law of Charles.* It means that the pressure of every gas will increase $\frac{1}{273}$ of its pressure at zero for every degree rise in temperature if the volume is kept constant.

From the definition of absolute temperature (p. 194) and from Charles's law we learn that for all gases at constant volume *pressure is proportional to absolute temperature*; that is,

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}. \tag{2}$$

When we arrange the experiment so that the gas can expand as the temperature rises, the pressure remaining constant, we obtain *the volume coefficient of expansion,* which is defined as *the ratio between the increase in volume per degree and the total volume of the gas at 0° C.* This was first done for different gases in 1802 by another Frenchman, Gay-Lussac, who found that *all gases have the same volume coefficient of expansion,* this coefficient being the same as the pressure coefficient, namely, $\frac{1}{273}$. This is known as *the law of Gay-Lussac.* It means that the volume of every gas will increase $\frac{1}{273}$ of its volume at zero for every degree rise in temperature, if the pressure is kept constant.

From the definition of absolute temperature (see page 194) and from Gay-Lussac's law we learn that for all gases at constant pressure *volume is proportional to absolute temperature*; that is,

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}. \tag{3}$$

If pressure, temperature, and volume all vary, we have

$$\frac{P_1 V_1}{P_2 V_2} = \frac{T_1}{T_2}, \quad \text{or} \quad V_2 = V_1 \frac{P_1 T_2}{P_2 T_1}.* \tag{4}$$

Any one of these six quantities may be found if the other five are known.

If the volume remains constant, that is, if $V_1 = V_2$, equation (4) reduces to (2), that is, to Charles's law. If the pressure remains constant, $P_1 = P_2$ and equation (4) reduces to (3), that is, to Gay-Lussac's law. If the temperature does not change, $T_1 = T_2$ and equation (4) reduces to $P_1 V_1 = P_2 V_2$, that is, to Boyle's law. If the ratio of densities instead of volumes is sought, it is only necessary to replace V_1/V_2 in (3) and (4) by D_2/D_1.

Equation (4) will be used frequently by the student of chemistry. Often he generates gases, such as hydrogen and oxygen, and measures their volume. Before he can use this in his calculations, he must find out what volume the gases would occupy under standard conditions of pressure and temperature (76 centimeters and 0° C.). Knowing the temperature and pressure existing in the laboratory at the time of his experiment, he can quickly make the change by substituting values in the above formula and solving for V_2.

Summary. The law of Charles. **The pressure coefficients of expansion of all gases are the same and are equal to $\frac{1}{273}$.**

The law of Gay-Lussac. **The volume coefficients of expansion of all gases are the same and are equal to $\frac{1}{273}$.**

QUESTIONS AND PROBLEMS

[In the problems below remember to express the temperatures on the absolute scale.]

A

1. How is gas pressure explained by the kinetic theory of matter?
2. How is the law of Gay-Lussac illustrated in baking bread?

* If equation (4) is not clear to the student, let him recall that if the speeds of two runners are the same, then their distances are proportional to their times, that is, $D_1/D_2 = t_1/t_2$; but if their times are the same and their speeds different, $D_1/D_2 = s_1/s_2$. If, now, one runs both twice as fast and twice as long, he evidently goes four times as far; that is, if time and speed both vary, $D_1/D_2 = t_1 s_1/t_2 s_2$.

3. Why is it unsafe to let a pneumatic inkstand like the one in Fig. 38 remain in the sun?

4. To what temperature must a cubic foot of gas at 0° C. be raised in order to double its volume, the pressure remaining constant?

5. If the volume of a quantity of air at 30° C. is 200 cm^3, at what temperature will its volume be 300 cm^3, the pressure remaining the same?

6. If the pressure on 15 cm^3 of air changes from 76 cm to 40 cm, the temperature remaining constant, what does its volume become? (See Boyle's law, p. 56.) If the temperature of the same gas then changes from 15° C. to 100° C., the pressure remaining constant, what will be the final volume?

B

1. The air within a half-inflated balloon occupies a volume of 100,000 l. The temperature is 15° C. and the barometric height is 75 cm. What will be its volume after the balloon has risen to the height of Mont Blanc, where the pressure is 37 cm and the temperature is – 10° C.?

2. From the law of Charles would you infer that the pressure of a body of gas becomes nothing at absolute zero? Why?

3. A tire gauge reads 35 lb/in.^{2} when applied to an automobile tire at 10° C. What will the pressure read at 35° C., it being assumed that the volume remains constant? (A tire gauge reads the difference in pressure between the air in the tire and the air outside. To get the total pressure, what must you add?) Can you see why an old tire might blow out on a hot day after a long run?

4. A chemistry student collects 500 cm^3 of oxygen when the barometer reads 740 mm and the temperature is 20° C. Find what volume the gas would have under standard conditions.

5. Two liters of air at atmospheric pressure and at 20° C. are heated until the volume and the pressure are both doubled. What is the temperature of the air?

Expansion of Liquids and Solids

Expansion of liquids. The expansion of liquids differs from that of gases in the following respects:

1. The coefficients of expansion of liquids are all considerably smaller than those of gases.

2. Different liquids expand at wholly different rates; for example, the coefficient of alcohol between 0° and 10° C. is .0011, of ether .0015, of petroleum .0009, of mercury .000181.

3. The same liquid often has different coefficients at different temperatures; that is, the expansion is irregular. Thus, if the coefficient of alcohol is obtained between 0° and 60° C., instead of between 0° and 10° C., it is .0013 instead of .0011.

The coefficient of mercury, however, is very nearly constant through a wide range of temperature, which, indeed, might have been inferred from the fact that mercury thermometers agree so well with gas thermometers.

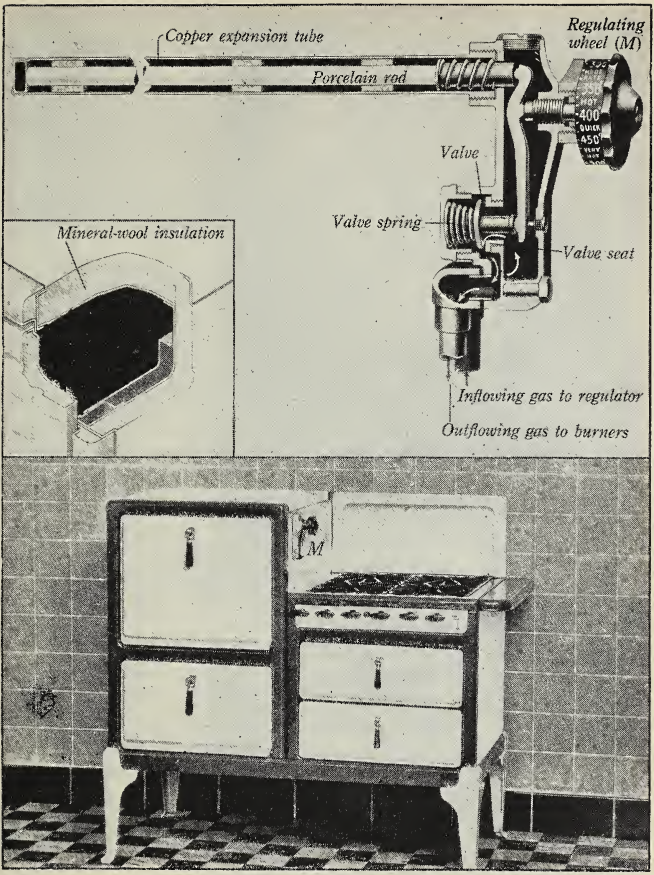
Fig. 175. Bulb for investigating expansions of liquids

Methods of measuring the expansion coefficients of liquids. One of the most convenient and common methods of measuring the expansion coefficients of liquids is to place the liquids in bulbs of known volume provided with capillary necks of known diameter, like the one shown in Fig. 175, and then to watch the rise of the liquid in the neck for a given rise in temperature. A certain allowance must be made for the increase in volume of the bulb, but this can readily be done if the coefficient of expansion of the substance of which the bulb is made is known.

Maximum density of water. When water is treated in the way described in the preceding paragraph, it reaches its lowest position in the stem at 4° C. As the temperature falls from that point down to 0° C., water exhibits the peculiar property of *expanding* with *a decrease* in temperature.

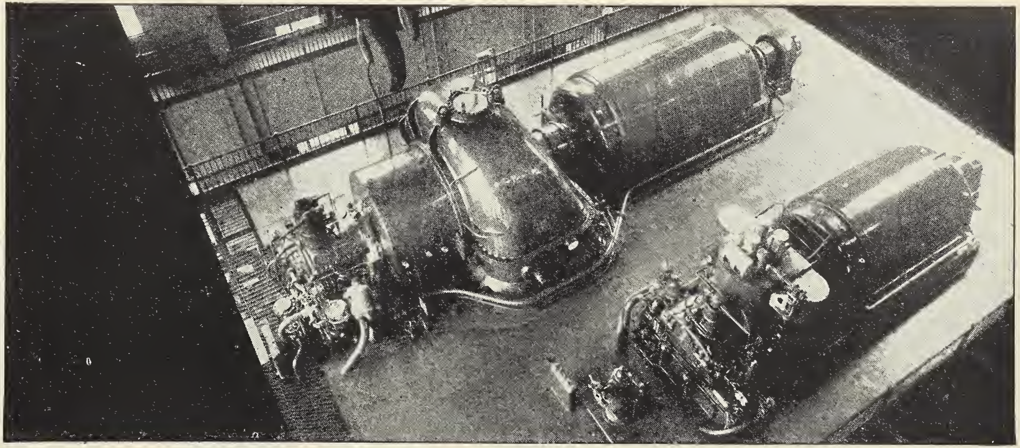
We learn, therefore, that *water has its maximum density at a temperature of 4° C.*

The cooling of a lake in winter. The preceding paragraph makes it easy to understand the cooling of any large body of water with the approach of winter. The surface layers are first cooled and contract. Being then heavier than the lower layers, they sink and are replaced by the warmer water from beneath. This process of cooling at the surface and sinking



Lorain Oven-Heat Regulator

The differential expansion between the copper expansion tube and the porcelain rod, which goes inside the oven, regulates the flow of gas through the valve and thus holds the temperature constant at any point determined by the setting of the regulating wheel (see *M*). Nearly all modern stoves are now using some such device. (Courtesy of the American Stove Company)



Rittase

A Modern, highly Efficient, High-Pressure, All-Steam Power Plant at Deepwater, New Jersey

This quiet 140,000-kilowatt steam plant operates with a steam pressure of 1230 pounds per square inch, at a temperature of 706° F. It is as efficient as any steam plant in the world today and is unexceeded by any Diesel plant. It had a mean performance in 1934 of 11,850 B.T.U. per kilowatt-hour. This means that year in and year out 28.9 per cent of the heat of combustion of the coal is in this plant transformed into work. The combined "mercury-steam" station of the Hartford Electric Light Company, built by the General Electric Company, had a mean performance for 1932, 1933, and 1934 of 10,500 B.T.U. per kilowatt-hour, or 32.5 per cent thermal efficiency. This is more than twice the highest efficiency that had been attained thirty years ago, and is the reason why light-and-power costs have come down so rapidly in the United States. (Courtesy of the American Gas and Electric Company)

goes on until the whole body of water has reached a temperature of 4° C. After this condition has been reached, further cooling of the surface layers makes them *lighter* than the water beneath, and they now remain on top until they freeze (Fig. 176). Consequently, before any ice whatever can form on the surface of a lake, the whole mass of water to the very bottom must be cooled to 4° C. This is why it requires a much longer and more severe period of cold to freeze deep bodies of water than to freeze shallow bodies. Furthermore, since the circulation described above ceases at 4° C., practically all the unfrozen water will be at 4° C. even in the coldest weather. Only the water which is in the immediate neighborhood of the ice will be lower than 4° C. This fact is of vital importance in the preservation of aquatic life.

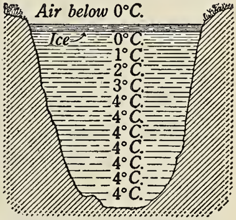


FIG. 176. Freezing of a deep lake

Expansion of solids. Proofs of the expansion of solids with an increase in temperature may be seen on every side. Railroad rails are laid with spaces between their ends so that they may expand during the heat of summer without crowding each other out of place. Wagon tires are made smaller than the wheels which they are to fit. They are then heated until they become large enough to be driven on, and in cooling they shrink again and thus grip the wheels with immense force.

Concrete roads are laid in sections with a layer of tar or asphalt in the cracks between to "take up" the tremendous force of the expansion. In the early days of road-building failure to do this was followed on a hot summer day by an upheaval of the pavement.

The steel framework of bridges and office buildings is put together with red-hot rivets. Their shrinkage on cooling draws the parts together with a tremendous force.

A common lecture-room demonstration of expansion is the following:

Heat in a Bunsen flame the ball B, which when cool just slips through the ring R. It will now be found too large to pass through the ring; but if the ring is heated, or if the ball is again cooled, it will pass through easily. (See Fig. 177.)

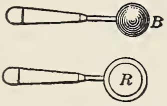


FIG. 177. Expansion of solids

If the expansion of gases and liquids is caused by an increase in the average kinetic energy of agitation of their molecules, the foregoing experiment with solids must clearly be given a similar interpretation. In a word, then, the temperature of a given substance, be it a solid, a liquid, or a gas, is determined by the average kinetic energy of agitation of its molecules.

Linear coefficients of expansion of solids. Since some substances expand more than others, it is necessary to measure experimentally the exact rate of expansion of each one. It is often more convenient to measure the increase in length of one edge of an expanding solid than to measure its increase in volume.

The amount which a *unit* length of any solid expands for *one* degree rise in temperature is called the linear coefficient of expansion of that solid. Thus, if a metal bar 100 centimeters long (l_1) at 0° C. (t_1) expanded to 101 centimeters (l_2) when heated to 100° C. (t_2), the expansion of *one* centimeter for *one* degree would be $\frac{101-100}{100(100-0)} = .0001$ centimeter. This is the coefficient (k) for this metal. Expressing this in letters instead of figures, so that it will cover any general case, we have

$$k = \frac{l_2 - l_1}{l_1(t_2 - t_1)}. \qquad (5)$$

From this formula we see that the coefficient may also be defined as the ratio of the increase in length per degree rise in temperature to the original length, or the fraction of its length by which it expands for one degree rise in temperature.

The difference in the linear coefficients of expansion of two substances like brass and iron, for example, may be illustrated as follows:

The bar of Fig. 178 consists of two strips, one of brass and one of iron, riveted together. Place it edgewise in a Bunsen flame so that both metals are heated equally. The bar bends as indicated in

FIG. 178

FIG. 179

Unequal expansion of metals

Fig. 179, showing that the more expansible metal, the brass, is on top. Plunge the bar into snow or ice, and it bends in the opposite direction.

The linear coefficients of a few common substances are given in the following table. The value .000012 as given for iron means, for instance, that a foot of iron will expand twelve millionths of a foot for one degree centigrade rise in temperature, or one mile will expand twelve millionths of a mile per degree centigrade rise in temperature.

Quartz	.0000005	Steel	.000013
"Invar" steel ($\frac{3}{10}$ nickel)	.0000009	Nickel	.000013
Glass (pyrex)	.000003	Copper	.000017
Glass (ordinary)	.000009	Brass	.000019
Platinum	.000009	Silver	.000019
Iron	.000012	Aluminum	.000023
Concrete	.000012	Zinc	.000029

Applications of Expansion

Compensated balance wheel. In the balance wheel of an accurate watch (Fig. 180) another application of the unequal expansion of metals is made. Increase in temperature both increases the radius of the wheel and weakens the elasticity of the spring which controls it. Both these effects tend to make the watch lose time. This tendency may be counteracted by bringing the mass of the rotating parts in toward the center of the wheel. This is accomplished by making the arcs *bc* of metals of different expansion coeffi-

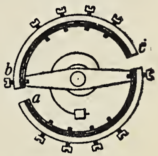


FIG. 180. Compensated balance wheel

cients, the inner metal (shown in black in the figure) having the smaller coefficient. The free ends of the arcs are then sufficiently pulled in by a rise in temperature to counteract the retarding effects. The principle is precisely the same as that which was simply illustrated in the compound bar shown in Fig. 178.

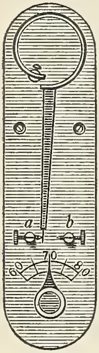


FIG. 181. The thermostat

The common thermostat (Fig. 181) is a compound bar of brass and "Invar" steel so arranged as to open the drafts by closing an electrical circuit at a when it is too cold and to close the drafts by making contact at b when it is too warm.

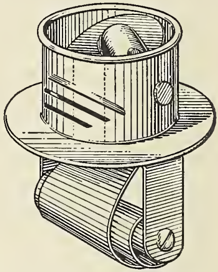


FIG. 182. Thermostat used in water system of an automobile

Automobile thermostats. Since an automobile engine runs more efficiently at a high temperature, it is desirable to warm it up as quickly as possible and to keep it at the high temperature, in winter as well as in summer. In modern automobiles this is accomplished by a thermostat (Fig. 182), placed between the engine and the radiator. When the engine is cold, the butterfly valve is closed, retarding the flow of water to the radiator. As the water gets hot, the unequal expansion of the two metals in the coiled spring opens the valve to allow a free flow of water.

Summary. The volume coefficient of expansion of any substance is the ratio of the increase in volume per degree rise in temperature to the initial volume (strictly the volume at zero).

The linear coefficient of expansion of a solid is the ratio of the increase in length per degree to the initial length (strictly the length at zero).

Differences in the coefficients of expansion of different solids are made use of in a variety of ways: for control of timepieces, for temperature regulation, for measurement of temperature, etc.

QUESTIONS AND PROBLEMS

A

1. Why is a thick tumbler more likely to break when hot water is poured into it than a thin one?

2. Why does pyrex glass (oven glass) not break when suddenly removed from the oven to a cold table? (See table, p. 203.)

3. Chemical vessels (beakers, test tubes, dishes, etc.) are sometimes made of pure quartz. They may be heated red-hot and then plunged into water without breaking. How do you account for this?

4. Give three reasons why mercury is a better liquid to use in thermometers than water.

5. Why may a glass stopper sometimes be loosened by pouring hot water on the neck of a bottle?

6. Should the pendulum of a clock be made longer or shorter in winter? Give reasons for your answer.

7. Explain how you could make at home a fire alarm for your basement.

8. Describe how a thermostat regulates house temperature.

9. The dial thermometer is a compound bar (Fig. 183) with iron on the outside and brass on the inside. A thread t is wound about the central cylinder c. Explain the action.

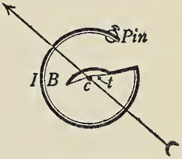


FIG. 183

10. The steel cable from which Brooklyn Bridge hangs is more than a mile long. By how many feet does a mile of its length vary between a winter day when the temperature is $-20°$ C. and a summer day when it is $30°$ C.?

B

1. A 50-foot steel tape is correct at 20° C. (*a*) What will be the error if it is used on a day when the temperature is 30° C.? (*b*) From the table on page 203 could you suggest a better material for the tape?

2. How much space must be left between steel rails 30 ft long if they are used in a locality where the yearly temperature variation is from $-10°$ C. to 40° C.?

3. The changes in temperature to which long lines of steam pipes are subjected make it necessary to introduce "expansion

joints." These joints consist of brass collars fitted tightly by means of packing over the separated ends of two adjacent lengths of pipe. If the pipe is of iron, and such a joint is inserted every 200 ft, and if the range of temperature which must be allowed for is from − 30° C. to 125° C., what is the minimum play which must be allowed for at each expansion joint?

4. If the span of a transmission line is 800 ft long at 0° C. and 800.704 ft long at 40° C., what is the coefficient of expansion of the wire?

5. When the bulb of a thermometer is placed in hot water, the mercury at first falls a trifle and then rises. Why?

6. Show from equation (5), p. 202, that linear coefficient of expansion may be defined as *increase in length per unit length per degree.*

7. If the variation of temperature throughout the year is 126° F., what space must be left between the ends of steel railroad rails 50 ft long laid in the coldest part of the year?

CHAPTER IX

Work and Heat Energy

*Mechanical Equivalent of Heat**

What becomes of wasted work? In all the devices for transforming work that we have considered we have found that on account of frictional resistances a certain per cent of the work expended upon the machine is wasted. The question which at once suggests itself is What becomes of this wasted work? The following familiar facts suggest an answer. When two sticks are vigorously rubbed together, they become hot; augers and drills often become too hot to hold; matches are ignited by friction; if a strip of lead is struck a few sharp blows with a hammer, it is appreciably warmed. Now, since we learned in Chapter VIII that, according to modern notions, increasing the temperature of a body means simply increasing the average velocity of its molecules, and therefore their average kinetic energy, the above facts point strongly to the conclusion that in each case the mechanical energy expended has been simply transformed into the energy of molecular motion. This view was first brought into prominence in 1798 by Benjamin Thompson, Count Rumford, an American by birth, who noticed that in the boring of cannon heat was continuously developed. It was first carefully and accurately tested by the English physicist James Prescott Joule (1818–1889) in a series of epoch-making experiments which extended from 1842 to 1870. In order to understand these experiments we must first learn how heat quantities are measured.

* This subject should be preceded by a laboratory experiment upon the law of mixtures, and either preceded or accompanied by experiments upon specific heat and mechanical equivalent. See Experiments 23 and 24 in *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

Units of heat: the calorie and the British thermal unit. *The calorie (cal.) is the amount of heat required to raise the temperature of 1 gram of water through 1° C., and the British thermal unit (B.T.U.) is the amount of heat required to raise the temperature of 1 pound of water 1° F.* (One B.T.U. = 252 calories, and 3413 B.T.U. = 1 kilowatt-hour.) Thus, when 100 grams of water has its temperature raised 4° C., we say that 400 calories of heat has entered the water. Similarly, when 100 grams of water has its temperature lowered 10° C., 1000 calories has passed out of the water. If, then, we wish to measure, for instance, the amount of heat developed in a lead bullet when it strikes against a target, we have only to let the spent bullet fall into a known weight of water and to measure the number of degrees through which the temperature of the water rises. The product of the number of grams of water and its rise in temperature is, then, by definition, the number of calories of heat which has passed into the water.

It will be noticed that in the definition given above we have made no assumption as to *what heat is*. Previous to the nineteenth century, physicists generally held it to be an invisible, weightless fluid, the passage of which into or out of a body caused it to grow hot or cold. This view accounts well enough for the heating which a body experiences when it is held in contact with a flame or other hot body, but it has difficulty in explaining the heating produced by rubbing or pounding. Rumford's view accounts easily for this, as we have seen, and it accounts no less easily for the heating of cold bodies by contact with hot ones; for we have only to think of the hotter and therefore more energetic molecules of the hot body as communicating their energy to the molecules of the colder body in much the same way in which a rapidly moving billiard ball transfers part of its kinetic energy to a more slowly moving ball against which it strikes.

Joule's experiment on the heat developed by friction. Joule argued that if the heat produced by friction etc. is indeed merely mechanical energy which has been transferred to the molecules of the heated body, then the same number of

calories must always be produced by the disappearance of a given amount of mechanical energy; and this must be true, no matter whether the work is expended in overcoming the friction of wood on wood or of iron on iron, in flattening a bullet against a target, in compressing air in a tire pump, or in any other possible way. To see whether or not this was so he caused mechanical energy to disappear in as many ways as possible and measured in every case the amount of heat developed.

In his first experiment he caused paddle wheels to rotate in a vessel of water by means of falling weights *W* (Fig. 184). The amount of work done by gravity upon the weights in causing their descent through a distance *d* was equal to their weight *W* times this distance. If no useful work was done, this work was all expended in overcoming the resistance of the water to the motion of the paddle wheels through it; that is, it was wasted in eddy currents in the water. Joule measured the rise in the temperature of the water and found that the mean of his best three trials gave *427 gram-meters as the amount of work required to develop enough heat to raise a gram of water one degree. (This means that to raise a pound of water 1° F. requires the expenditure of 778 foot-pounds of work.) This value, confirmed by modern experiments, is now generally accepted as correct.* He then repeated the experiment, substituting mercury for water, and obtained 425 gram-meters as the work necessary to produce a calorie of heat. The difference between these numbers is less than was to have been expected from the unavoidable errors in the observations. He then devised an arrangement in which the heat

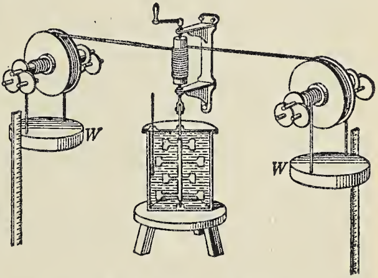


FIG. 184. Joule's first experiment on the mechanical equivalent of heat

was developed by the friction of iron on iron, and again obtained 425 gram-meters.

Heat produced by collision. If you attempted to pick up a bullet which had just struck a steel target, you would probably find that it was too hot to handle. A Frenchman named Hirn was the first to measure accurately the kinetic energy which disappears when heat is developed by collision. He allowed a steel cylinder to fall through a known height and crush a lead ball. The amount of heat developed in the lead was measured by observing the rise in temperature of a small amount of water into which the lead was quickly plunged. As the mean of a large number of trials he also found that 425 gram-meters of energy disappeared for each calorie of heat that appeared.

Heat produced by the compression of a gas. Another way in which Joule measured the relation between heat and work was by compressing a gas and comparing the amount of work done in the compression with the amount of heat developed.

Every bicyclist finds that his pump grows hot when he inflates his tires. Likewise power compression pumps for furnishing "free air" at gasoline filling stations become so hot in operation that they are equipped with circular "fins" to give a large surface for rapid radiation of the heat developed. This heat is due partly to the friction of the piston against the walls, but chiefly to the fact that the downward motion of the piston is transferred to the molecules which come in contact with it, so that the velocity of these molecules is increased. The principle is precisely the same as that involved in the velocity given a ball by a bat. If the bat is held still and a ball thrown against it, the ball rebounds with a certain velocity; but if the bat is moving rapidly forward to meet the ball, the latter rebounds with a much greater velocity. So the molecules which in their natural motions collide with an advancing piston rebound with greater velocity than they would if they had struck a fixed wall. This increase in the molecular velocity of a gas on

compression is so great that when a mass of gas at 0° C. is suddenly compressed to one half its volume, the temperature rises to 87° C.

[The effect may be strikingly illustrated by the fire syringe (Fig. 185). Place a few drops of carbon disulfide on a small bit of cotton, drop it to the bottom of the tube *A*, and then remove it; then insert the piston *B* and very suddenly push it down. Sufficient heat will be developed to ignite the vapor, and a flash will result. (If the flash does not result from the first stroke, withdraw the piston completely, then reinsert, and compress again.)

[To measure the heat of compression Joule surrounded a small compression pump with water, made 300 strokes on the pump, and measured the rise in temperature of the water. As the result of these measurements he obtained 444 gram-meters as the mechanical equivalent of the calorie. The experiment, however, could not be performed with great exactness.

FIG. 185. The fire syringe

[If compression produces heat, then when a gas expands, cooling ought to take place. When a motorist lets a little air out of a tire that has been inflated too much, he notices that the air rushing out feels very cool to his hand. Joule measured this effect also — the cooling produced when a gas pushes forward a piston and thus does work. He obtained 437 gram-meters.

Significance of Joule's experiments. Joule made three other determinations of the relation between heat and work by methods involving electrical measurements. He published as the mean of all his determinations 426.4 gram-meters as the mechanical equivalent of the calorie. But the value of his experiments does not lie primarily in the accuracy of the final results, but rather in the proof which they for the first time furnished that *whenever a given amount of work is wasted, no matter in what particular way this waste occurs, the same definite amount of heat always appears.*

One of the most accurate determinations of the mechanical

equivalent of heat was made by the American physicist Rowland (1848–1901) in 1880. *He obtained 427 gram-meters* (4.19×10^7 *ergs*). We will generally take it as 42,000,000 ergs. *The mechanical equivalent of 1 B.T.U. is 778 foot-pounds.*

Conservation of energy. We are now in a position to state the law of all machines in its most general form, that is, in such a way as to include even the cases where friction is present. It is this: *The work done by the acting force is equal to the sum of the kinetic and potential energies stored up plus the mechanical equivalent of the heat developed.*

In other words, *whenever energy is expended on a machine or device of any kind, an exactly equal amount of energy always appears either as useful work or as heat.* The useful work may be represented in the potential energy of a lifted mass, as when water is pumped up to a reservoir; or in the kinetic energy of a moving mass, as when a stone is thrown from a sling; or in the potential energies of molecules whose positions with reference to one another have been changed, as when a spring has been bent; or in the molecular potential energy of chemically separated atoms, as when an electric current separates a compound substance. The *wasted* work always appears in the form of increased molecular motion, that is, in the form of heat. This important generalization has received the name of *the principle of the conservation of energy.* It may be stated thus: *Energy may be transformed, but it can never be created or destroyed.*

Perpetual-motion machines. Some of us occasionally try to "get something for nothing." In all ages men have tried to invent a machine out of which they could obtain work continuously without expending upon it an equivalent amount of work — that is, a perpetual-motion machine. Thousands of patents were granted in the past for ingenious mechanical and electric devices which looked, on paper, as though they might work. Since the Patent Office has adopted the policy of requiring working models with all applications for such patents, not one patent has been granted on such a device. Fig. 186 shows two of these attempts, as exhibited at the

Century of Progress Exposition at Chicago. When actually tried, they do not work unless a small amount of power is applied to the pulley from outside. Why not?

The principle of the conservation of energy absolutely denies the possibility of the existence of such a device. For only in case there is no heat developed, that is, in case there are no frictional losses, can the work taken out be equal to the work put in, and in no case can it be greater. Since, in fact, there are always some frictional losses, the principle of the conservation of energy asserts that it is impossible to make a machine which will keep itself running forever, even though it does no useful work; for no matter how much kinetic or potential energy is imparted to the machine to begin with, there must always be a continuous drain upon this energy to overcome frictional resistances, so that, as soon as the wasted work has become equal to the energy put in, the machine must stop.

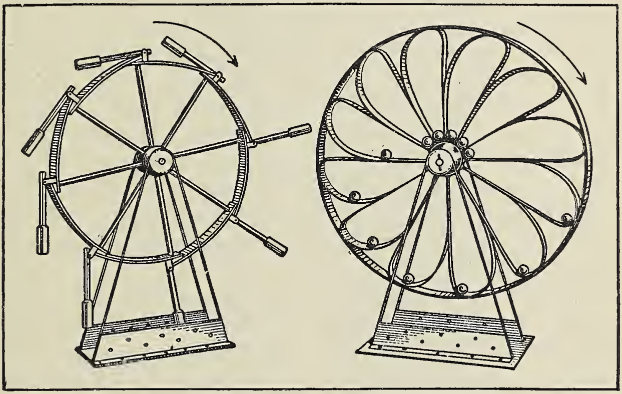


FIG. 186. Models of perpetual-motion machines

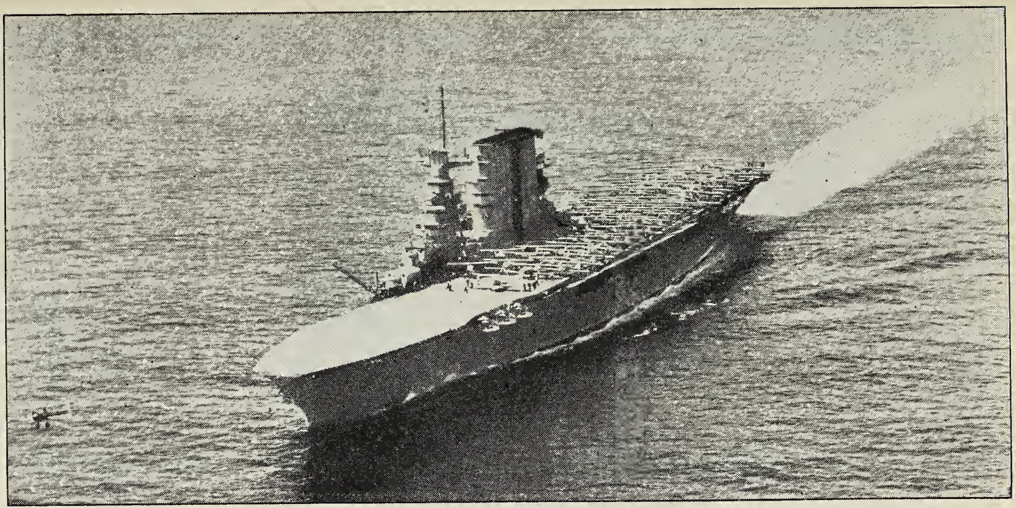
The principle of the conservation of energy has now gained universal recognition and has taken its place as the cornerstone of all physical science. Einstein (see opposite page 75)

has recently suggested, however, that matter may be converted into the energy of motion or actually into the energy of radiation, and there is now a good deal of experimental evidence in favor of this view.

Transformations of energy in a power plant. The transformations of energy which take place in any power plant, such as that at Niagara, are as follows: The energy first exists as the potential energy of the water at the top of the falls. This is transformed in the turbine pits into the kinetic energy of the rotating wheels. These turbines drive dynamos in which there is a transformation into the energy of electric currents. These currents travel on wires as far as Syracuse, 150 miles away, where they run streetcars and other forms of motors. The principle of conservation of energy asserts that the work which gravity did upon the water in causing it to descend from the top to the bottom of the turbine pits is exactly equal to the work done by all the motors, plus the heat developed in all the wires and bearings and in the eddy currents in the water.

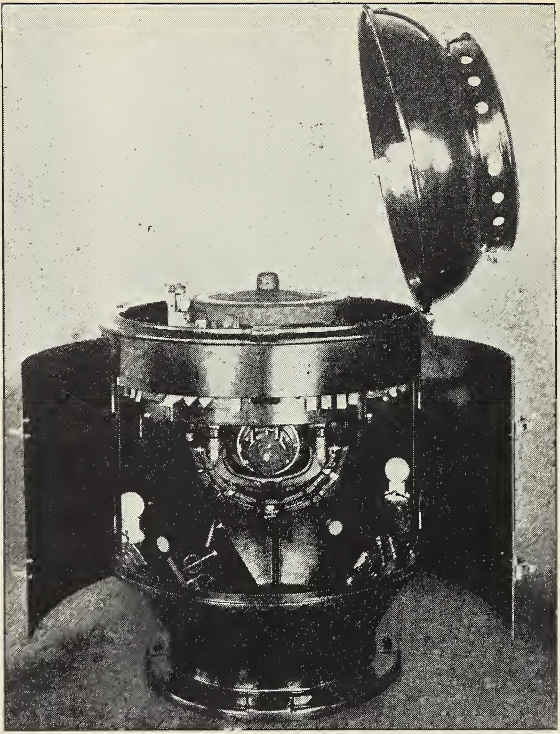
Let us next consider where the water at the top of the falls obtained its potential energy. Water is being continually evaporated at the surface of the ocean by the sun's heat. This heat imparts sufficient kinetic energy to the molecules to enable them to break away from the attractions of their fellows and to rise above the surface in the form of vapor. The lifted vapor is carried by winds over the continents and precipitated in the form of rain or snow. Thus the potential energy of the water above the falls at Niagara is simply transformed heat energy of the sun. If in this way we analyze any available source of energy at man's disposal, we find in almost every case that it is directly traceable to the sun's heat as its source. Thus the energy contained in coal is simply the energy of separation of the oxygen and carbon which were separated in the processes of growth. This separation was effected by the sun's rays.

The earth is continually receiving energy from the sun at the rate of 232,000,000,000,000 horsepower, or about a



Airplane-Carrier

The airplane-carrier has a flat deck for the take-off and landing of airplanes. The space below this deck functions as a hangar. Elevators raise and lower the planes. Below decks there are also machine shops and other repair facilities. The mast, funnels, and guns of the ship may be placed at the side, as shown in the above illustration. The first aircraft-carriers, developed toward the end of the First World War, were converted cruisers. The first in the United States was the *Langley*, placed in service in 1922. (Courtesy of U. S. Navy)



Gyrocompass

The Sperry gyrocompass (1911) has the advantage over the magnetic compass of pointing due north instead of "magnetic north" and of being uninfluenced by the magnetic disturbances which arise in steel ships. In very large measure the magnetic compass has become, at least for large ships, merely an auxiliary to be used in case of a breakdown of the gyrocompass. The gyrocompass makes use of a gyroscope wheel which rotates in the same direction as the rotation of the earth. The gyro wheel is rotated at a moderately high speed by electricity. The axis maintains a true north-south direction. At various points in the ship, repeater compasses may show the direction indicated by the gyrocompass. A course-recorder and an automatic gyro-pilot may also be attached. (Courtesy of Sperry Gyroscope Company, Inc.)

seventh of a million horsepower per inhabitant. We can form some conception of the enormous amount of energy that the sun radiates in the form of heat by reflecting that the amount received by the earth is not more than $\frac{1}{2,000,000,000}$ of the total given out. Of the amount received by the earth not more than $\frac{1}{1000}$ part is stored up in animal and vegetable life and lifted water. This is practically all the energy which is available on the earth for man's use.

Summary. The calorie is the amount of heat required to raise the temperature of 1 gram of water through 1° C.

The British thermal unit (B.T.U.) is the amount of heat required to raise the temperature of 1 pound of water through 1° F.

One B.T.U. = 252 calories; 3413 B.T.U. = 1 kilowatt-hour.

Joule proved that heat has a mechanical equivalent by experimentally showing that whenever a given amount of work is transformed into heat, no matter in what particular way this transformation occurs, the same definite amount of heat always appears.

The mechanical equivalent of 1 calorie is 42,000,000 ergs (= 427 gram-meters).

The mechanical equivalent of 1 B.T.U. is 778 foot-pounds.

General law of all machines where friction is present and velocity imparted to mass. The work done by the acting force is equal to the sum of the kinetic and potential energies stored up plus the mechanical equivalent of the heat developed; or, whenever energy is expended on a machine or device of any kind, an exactly equal amount of energy always appears either as useful work or as heat.

QUESTIONS AND PROBLEMS

A

1. How does a Boy Scout make a fire without matches?

2. A golf ball weighing 45 g dropped 200 cm on a marble step and rebounded 150 cm. (*a*) How many gram-centimeters of mechanical energy disappeared? (*b*) Into what form of energy did it change, and where was this energy located?

3. Explain the fact that the principle of conservation of energy could not have been discovered before means were devised to measure heat.

B

1. The kinetic energy of mass motion of an automobile running 20 mi/hr was 37,344 ft-lb. In stopping this car how many B.T.U. were developed in the brakes?

2. Two and a half gallons of water (= 20 lb) was warmed from 68° F. to 212° F. If the heat energy put into the water could all have been made to do useful work, how high could 10 t of coal have been hoisted?

3. (*a*) Explain why the cylinder of an automobile-tire pump becomes hot when the pump is being used. (*b*) Why is the air cooled as it escapes from the valve of an automobile tire?

4. Show that the principle of conservation of energy makes it necessary that a body of gas should cool on expanding.

5. An advertisement states that a gallon of gasoline could lift a 75-ton whale 660 ft. If gasoline contains 126,000 B.T.U. per gallon, check the accuracy of this statement.

6. Meteorites are small, cold bodies moving about in space. Why do they become luminous when they enter the earth's atmosphere?

7. Analyze the transformations of energy which occur when a bullet is fired vertically upward.

8. Show that the energy of a waterfall is merely transformed solar energy.

9. In an experimental determination of the mechanical equivalent of heat it was estimated that the temperature of 100 g of water was raised 5.85° C. by the work done by a mass of 10 kg falling 25 m. Calculate the mechanical equivalent of heat.

10. In an encyclopedia read an article on perpetual-motion machines. Try to see why each fails to work.

Specific Heat

Definition of specific heat. It is necessary to make a clear distinction between the temperature of a body (measured in degrees) and the amount of heat that it contains (measured in calories). A cup of boiling water poured from a teakettle has the same temperature as the water in the kettle, but the amount of heat in the kettle is many times that in the cup. The temperature of a body depends only on the average

kinetic energy of its molecules, but the quantity of heat in it depends not only on its temperature and its mass but also on *the kind of material,* as will be shown by the following experiment:

Heat in separate test tubes 100 g each of lead shot, iron wire, and aluminum wire by placing the test tubes in boiling water for ten or fifteen minutes. Provide three metal cans, called calorimeters (heat-measurers), each containing 100 g of water at room temperature. Pour the heated shot into the first calorimeter and, after thorough stirring, note with a thermometer the total rise in temperature. Do the same with the other metals. The aluminum will be found to raise the temperature about twice as much as the iron, and the iron about three times as much as the lead. Therefore about six times as much heat must have passed out of the aluminum as out of the lead; that is, each gram of aluminum in cooling 1° C. gives out about six times as many calories as a gram of lead.

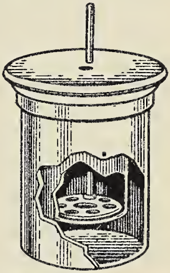


FIG. 187. Calorimeter

The number of calories taken up by 1 gram of a substance when its temperature rises through 1° C., or given up when it falls through 1° C., is called the specific heat of that substance.

It will be seen from this definition and the definition of the calorie (p. 208) that the specific heat of water is 1.

Since this is true, we can also define specific heat as the ratio of the amount of heat required to raise the temperature of a mass of a substance a certain number of degrees to the amount of heat required to raise the temperature of an equal mass of water the same number of degrees. (Compare this definition with that of specific gravity, p. 19.)

[**Determination of specific heat by the method of mixtures.** The preceding experiment illustrates a method for measuring accurately the specific heats of different substances; for, in accordance with the principle of the conservation of energy, when hot and cold bodies are mixed, as in these experiments, so that heat energy passes from one to the other.

the gain in the heat energy of one must be just equal to the loss in the heat energy of the other.

❲This method is by far the most common one for determining specific heats. It is known as the *method of mixtures.* Suppose, to take an actual case, that the initial temperature of the shot used in the demonstration on page 217 was 95° C. and that of the water 19.7°, and that, after mixing, the temperature of the water and shot was 22°. Then, since 100 grams of water has had its temperature raised through $22° - 19.7° = 2.3°$, we know that 230 calories of heat has entered the water. Since the temperature of the shot fell through $95° - 22° = 73°$, the number of calories given up by the 100 grams of shot in falling 1° was $\frac{230}{73} = 3.15$. Hence the specific heat of lead, that is, *the number of calories of heat given up by 1 gram of lead when its temperature falls 1° C.*, is $3.15/100 = .0315$.

❲Or, again, we may work out the problem algebraically as follows: Let x equal the specific heat of lead. Then the number of calories which comes out of the shot is *its mass times its specific heat times its change in temperature*, that is, $100 \times x \times (95 - 22)$; and, similarly, the number which enters the water is the same, namely, $100 \times 1 \times (22 - 19.7)$. Hence we have

$$100(95 - 22)x = 100(22 - 19.7), \text{ or } x = .0315.$$

❲By experiments of this sort the specific heats of some of the common substances have been found to be as follows:

TABLE OF SPECIFIC HEATS

Lead	.0315	Iron and steel	.113
Gold	.0316	Glass	.2
Platinum	.032	Earth, rock, sand (about)	.2
Mercury	.0333	Aluminum	.218
Silver	.0568	Steam	.46
Brass	.094	Alcohol	.5
Copper	.095	Ice	.504

❲When we buy coal, we are really buying calories or B.T.U., not tons. Large purchasers buy their coal on rigid

specifications, requiring a certain minimum number of B.T.U. per pound. A sample of coal from each carload is burned in a calorimeter to see if the fuel comes up to the specifications.

Food calories. When food is taken into the body, it is oxidized (burned) to produce energy, which is also measured in calories. Dietitians use the large calorie (often written and printed "Calorie," with the abbreviation "Cal") — the amount of heat necessary to raise 1 *kilogram* of water 1° C. To say that a large slice of bread gives 100 Calories means that it will give the body as much heat as would be necessary to raise 1 kilogram of water through 100° C.

Approximate Heat Values of Fuels

Substance	Heat Values	
	Large Calories per Kilogram	B. T. U. per Pound
Carbon	7,860	14,200
Charcoal	8,100	14,600
Coal, anthracite	7,480 to 8,580	13,500 to 15,300
Coal, bituminous	6,600 to 7,920	11,700 to 14,400
Coke	7,590 to 8,140	13,700 to 14,500
Hydrogen	34,460	62,030
Lignite	3,360 to 7,260	7,200 to 11,700
Peat	3,360 to 5,060	7,200 to 9,000
Petroleum	11,000	20,000
Wood, ash	4,710	8,480
Wood, beech	4,754	8,590
Wood, elm	4,730	8,510
Wood, oak	4,620	8,316
Wood, pine	5,084	9,153

Summary. **The specific heat of a substance is the number of calories taken up by 1 gram of the substance when its temperature rises through 1° C.**

The number of heat units lost or gained by a body equals its mass times its change in temperature times its specific heat.

To find specific heat by the method of mixtures, equate the heat lost by the cooling body to the heat gained by the warming body.

Calorimeters are used to find the energy values of fuels and foods.

QUESTIONS AND PROBLEMS

A

1. The specific heat of water is much greater than that of any other liquid or of any solid. Explain how this accounts for the fact that the temperature changes of an island in mid-ocean are less extreme than those of an inland region.

2. A barrelful of lukewarm water, when poured into a snowdrift, melts much more snow than a cupful of boiling water does. Which has the greater quantity of heat?

3. Which would be heated more, a lead or a steel bullet, if they were fired against a target with equal speeds?

4. Which would make a better foot-warmer, a pound of boiling water or a pound of iron at the same temperature? Why?

5. Why is iron, rather than other metals, used for ironing clothes? (See the "Table of Specific Heats," p. 218.)

6. Why does the sand on a beach become hotter than the water?

7. Why does the land usually become colder at night than the water in an adjoining pond or lake?

8. How many calories are required to heat a laundry iron weighing 3 kg from 20° C. to 130° C.?

9. How many B.T.U. are required to heat a 6-pound fireless-cooker stone from 68° F. to 500° F. (specific heat of soapstone = .2)?

10. If 100 g of mercury at 95° C. is mixed with 100 g of water at 15° C., and if the resulting temperature is 17.6° C., what is the specific heat of mercury?

B

1. What happens to the cooling capacity of the automobile radiator when alcohol is added in wintertime? Why?

2. Two fields lie side by side, the one well drained, the other not. Which would be ready for planting earlier in the spring? Give one reason for this. (A certain minimum temperature is needed for seed germination.)

3. One hundred grams of brass is warmed 1° C. How much water could be warmed 1° C. by this same amount of heat? (This is called the water equivalent of the brass.)

4. If 200 g of water at 80° C. is mixed with 100 g of water at 10° C., what will be the temperature of the mixture? (Let x equal the final temperature; then $100(x - 10)$ cal is gained by the cold water, and $200(80 - x)$ cal is lost by the hot water.)

5. What temperature will result if 400 g of aluminum at 100° C. is placed in 500 g of water at 20° C.?

6. A piece of platinum weighing 10 g is taken from a furnace and plunged instantly into 40 g of water at 10° C. The temperature of the water rises to 24° C. What was the temperature of the furnace?

7. How many B.T.U. are required to warm a 6-pound laundry iron from 75° F. to 250° F.?

8. Eight pounds of water is placed in a copper kettle weighing 2.5 lb. (*a*) How many B.T.U. are required to heat the water and the kettle from 70° F. to 212° F.? (*b*) If 4.3 ft^3 of gas is used to do this, and if each cubic foot of gas on being burned yields 600 B.T.U., what is the efficiency of the heating apparatus?

9. A copper calorimeter of mass 200 g contains 150 g of water at 8° C.; 300 g of lead shot are transferred to the calorimeter from a cup which has been immersed for some time in boiling water. What temperature do the calorimeter and water attain?

10. A copper ball weighing 3 kg was heated to a temperature of 100° C. When placed in water at 15° C. it raised the temperature to 25° C. How many grams of water were there?

11. If the specific heat of lead is .031 and the mechanical equivalent of a calorie is 427 g-m, through how many degrees centigrade will a 1000-gram lead ball be raised if it falls from a height of 100 m, provided all the heat developed by the impact goes into the lead?

CHAPTER X

Change of State

*Fusion (Melting)**

Energy changes accompanying change of state. In discussing the molecular theory (see page 80) we learned that the molecules of which all substances are composed may exist in either the solid, the liquid, or the gaseous state, and that in these different states there are striking differences in both the spaces and the binding forces between these molecules. It will, then, be interesting to find what energy changes accompany a change in state.

Heat of fusion. If on a cold day in winter a quantity of snow is brought in from out of doors when the temperature is below 0° C. and placed over a source of heat, a thermometer plunged into the snow will be found to rise slowly until the temperature reaches 0° C., when it will become stationary and remain so during all the time the snow is melting, provided only that the contents of the vessel are continuously and vigorously stirred. As soon as the snow is all melted, the temperature will begin to rise again.

Since the temperature of ice at 0° C. is the same as the temperature of water at 0° C., it is evident from this experiment that the heat which changes ice to water produces no change in the average kinetic energy of its molecules. This energy must therefore be used up in pulling apart the molecules of the crystals of which ice is composed, and thus reducing the ice to a form in which the molecules are held together less closely, that is, to the liquid form. In other

* This subject should be preceded by a laboratory exercise on the curve of cooling through the point of fusion, and followed by a determination of the heat of fusion of ice. See, for example, Experiments 25 and 26 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

words, the energy which existed in the flame as the kinetic energy of molecular motion has been transformed, upon passage into the melting solid, into the potential energy of molecules which have been pulled apart against the force of their mutual attraction. *The number of calories of heat energy required to melt 1 gram of any substance without producing any change in its temperature is called the heat of fusion of that substance.*

Numerical value of heat of fusion of ice. Since it is found to require about 80 times as long for a given flame to melt a quantity of snow as to raise the melted snow through 1° C., we conclude that it requires about 80 calories of heat to melt 1 gram of snow or ice. This constant is, however, much more accurately determined by the method of mixtures. Thus suppose that a piece of ice weighing 131 grams is dropped into 500 grams of water at 40° C., and suppose that after the ice is all melted the temperature of the mixture is found to be 15° C. The number of calories which have come out of the water is $500 \times (40 - 15) = 12{,}500$. But $131 \times 15 = 1965$ calories of this heat must have been used in raising the water from the melted ice from 0° C. to 15° C. The remainder of the heat, namely, $12{,}500 - 1965 = 10{,}535$, must have been used in melting the 131 grams of ice. Hence the number of calories required to melt 1 gram of ice is $\frac{10{,}535}{131} = 80.4$.

To state the problem algebraically, let $x =$ the heat of fusion of ice. Then we have

$$131\,x + 1965 = 12{,}500\text{; that is, } x = 80.4.$$

According to the most careful determinations the heat of fusion of ice is 80.0 calories per gram, or 144 B.T.U. per pound.

Energy transformation in fusion. Ordinarily when we apply heat to a body, its temperature rises, and we say that the average kinetic energy of the molecules is greater. Since the temperature of the water from the melted ice was the same as that of the ice, it is clear that the energy used in melting the ice produced no change in the kinetic energy of its molecules. This energy, 80 calories per gram, was used up in

pulling apart the molecules of the ice crystals, and giving them potential energy with respect to one another. It may be likened to the potential energy which is stored up in a kilogram weight (p. 171), or in a wound clockspring, where the molecules of steel are unnaturally separated on the outside of the spring and pushed together abnormally on the inside. *The heat which disappeared while the ice was melting represents the work done in producing the change of state,* and is the exact equivalent of the potential energy gained by the rearranged molecules. No energy was lost or gained in the exchange. This is strictly in accord with the law of the conservation of energy.

Heat given out when water freezes. Add snow and salt to a beaker of water until the temperature of the liquid mixture is as low as $-10°$ C. or $-12°$ C. Then thrust a test tube containing a thermometer and a quantity of pure water into the cold solution. If the thermometer is kept very quiet, the temperature of the water in the test tube will fall four or five or even ten degrees below 0° C. without producing solidification. But as soon as the thermometer is stirred or a small crystal of ice is dropped into the neck of the tube, the ice crystals will form with great suddenness, and at the same time the thermometer will rise to 0° C., where it will remain until all the water is frozen.

The experiment shows in a very striking way that the process of freezing is a heat-evolving process. This was to have been expected from the principle of the conservation of energy; for *since it takes 80 calories of heat energy to turn a gram of ice at 0° C. into water at 0° C., this amount of energy must reappear when the water turns back to ice.*

Use made of energy transformations in melting and freezing. Because of the high value of the heat of fusion of ice, it makes a good refrigerating agent. A refrigerator (Fig. 188) is a box with double walls filled with a good insulating material so as to make it difficult for heat to pass in from the outside. Ice is kept in the *upper* part of one compartment so as to cool the air at the top, which, because of its greater density when cool, settles and causes a circulation as indicated by

the arrows. For each gram of ice that melts, 80 calories disappear from the air and food within the refrigerator. It is the melting of the ice that does the cooling, and therefore the ice should never be covered with a wrapping to keep it from melting. The insulation should rather be in the outer walls, to prevent heat from entering from outside.

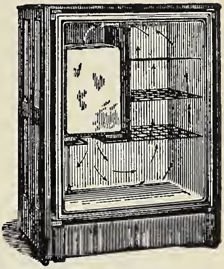


FIG. 188. A refrigerator

Standards have been set up for an efficient refrigerator. It should be of durable construction, with 2 inches or more of corkboard insulation or its equivalent (not cork dust). With an outside temperature of 75° F. it should maintain a temperature no higher than 45° F. in the milk compartment and 50° F. in the food compartment.

In many households electric or gas refrigerators have replaced ice refrigerators, owing to their convenience and more uniform cooling. (See opposite page 254.) Their cost of operation, however, is probably higher, if all factors, including current, depreciation, interest, and repairs, are taken into consideration.

The heat given off by the freezing of water is often turned to practical account; for example, tubs of water are sometimes placed in vegetable cellars to prevent the vegetables from freezing. The effectiveness of this procedure is due to the fact that the temperature at which the vegetables freeze is slightly lower than 0° C. As the temperature of the cellar falls, the water therefore begins to freeze first, and in so doing may give off enough heat to prevent the freezing of the vegetables.

It is partly because of the heat given off by the freezing of large bodies of water that the temperature never falls so low in the vicinity of large lakes as it does in inland localities.

Melting points of crystalline substances. If a piece of ice is placed in a vessel of boiling water for an instant and then removed and wiped, it will not be found to be in the slightest

degree warmer than a piece of ice which has not been exposed to the heat of the warm water. The melting point of ice is therefore a perfectly fixed, definite temperature, above which the ice can never be raised so long as it remains ice, no matter how fast heat is applied to it. All crystalline substances are found to behave exactly like ice in this respect, each substance of this class having its characteristic melting point. The following table gives the melting points of some of the commoner crystalline substances:

Gasoline . . .	(below) − 145° C.	Aluminum	650° C.
Mercury	− 39° C.	Copper	1100° C.
Ice	0° C.	Cast iron	1200° C.
Paraffin	54° C.	Platinum	1775° C.
Sulfur	114° C.	Iridium	1950° C.
Lead	330° C.	Tungsten	3390° C.

We may summarize the experiments upon melting points of crystalline substances in the two following laws:

1. *The temperatures of solidification and fusion are the same.*

2. *The temperature of the melting or solidifying substance remains constant from the moment at which melting or solidification begins until the process is completed.*

Fusion of noncrystalline, or amorphous, substances. Hold the end of a glass rod in a Bunsen flame. Instead of changing suddenly from the solid to the liquid state, it will gradually grow softer and softer until, if the rod is not too thick and the flame is sufficiently hot, a drop of molten glass will finally fall from the end of the rod.

If the temperature of the rod had been measured during this process, it would have been found to be continuously rising. Other noncrystalline substances, such as tar, wax, clay, celluloid, and "Bakelite," all act in a similar manner when softened by heat, and may be easily hammered, bent, or molded to any desired shape. Cast iron has a very definite melting point; hence it cannot be welded. On the other hand, two pieces of heated wrought iron, being noncrystalline, may easily be welded together under the blacksmith's hammer.

Change of volume on solidifying. The automobile-owner who forgets to put alcohol into his radiator in winter soon

learns, when he pays a large bill for a cracked engine block, that water expands when it solidifies. Unprotected water-pipes burst, and lawns "heave" so that in the spring it is necessary to press the roots down again with a heavy roller.

One cubic foot of water becomes 1.09 cubic feet of ice, thus expanding one eleventh of its original volume. This may seem strange in view of the fact that the molecules are certainly more closely knit together in the solid than in the liquid state (see page 131); but the strangeness disappears when we reflect that the molecules of water in freezing group themselves into crystals, and that this operation presumably leaves comparatively large free spaces between different crystals, so that, although groups of individual molecules are more closely joined than before, the total volume occupied by the whole assemblage of molecules is greater.

But the great majority of crystalline substances contract upon solidifying and expand upon liquefying. Water, antimony, bismuth, cast iron, and a few alloys containing antimony or bismuth are the chief exceptions. It is only from substances which expand, or which change in volume very little on solidifying, that sharp castings can be made; for it is clear that contracting substances cannot retain the shape of the mold. It is for this reason that gold and silver coins must be stamped rather than cast. Any metal from which type is to be cast must be one which expands upon solidifying, for it need scarcely be said that perfectly sharp outlines are indispensable to good type. Ordinary type metal is an alloy of lead, antimony, and copper, which fulfills these requirements.

Effect of the expansion of water in freezing. If water were not unlike most substances in that it expands on freezing, many, if not all, of the forms of life which now exist on the earth would be impossible; for in winter the ice would sink in ponds and lakes as fast as it froze, and soon our rivers, lakes, and perhaps our oceans also would become solid ice.

The force exerted by the expansion of freezing water is very great. Steel bombs have been burst by filling them with water

and exposing them on cold winter nights. One of the chief agents in the disintegration of rocks is the freezing and consequent expansion of water which has percolated into them.

Effect of pressure on melting point. Boys may have noticed that snowballs "pack" more readily on a warm day than on an extremely cold one, and may have wondered why. Since the outside pressure acting on the surface of a body tends to prevent its expansion, we should expect that any increase in the outside pressure would tend to prevent the solidification of substances which expand upon freezing. It ought therefore to require a lower temperature to freeze ice under a pressure of two atmospheres than under a pressure of one. Careful experiments have verified this conclusion and have shown that the melting point of ice is lowered .0075° C. for an increase of one atmosphere in the outside pressure. Although this lowering is so small a quantity, its existence may be shown as follows:

Press two pieces of ice firmly together beneath the surface of a vessel full of warm water. When taken out they will be found to be frozen together, in spite of the fact that the temperature of the water is much warmer than that of freezing.

The explanation is as follows: At the points of contact the pressure reduces the freezing point of the ice below 0° C., and hence it melts and gives rise to a thin film of water the temperature of which is slightly below 0° C. When this pressure is released, the film of water at once freezes, for its temperature is below the freezing point corresponding to ordinary atmospheric pressure. The same phenomenon may be even more strikingly illustrated by the following experiment:

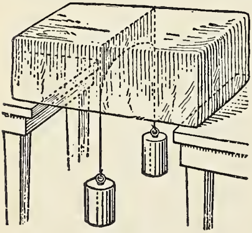


Fig. 189

Hang two weights of from 5 to 10 kg by a wire over a block of ice, as in Fig. 189. In an hour or less the wire will be found to have cut completely through the block, leaving the ice, however, as solid as at first.

The explanation is as follows: Just below the wire the ice melts because of the pressure; as the wire sinks through the layer of water thus formed, the pressure on the water is relieved and it immediately freezes again above the wire.

Geologists believe that the continuous flow of glaciers is partly due to the fact that the ice melts at points where the pressures become large, and freezes again when these pressures are relieved. This process of melting under pressure and freezing again as soon as the pressure is relieved is known as *regelation* ("refreezing").

On the other hand, substances which contract on solidifying (like paraffin) change from a liquid to a solid at a *higher* temperature when pressure is applied, since they are helped by the pressure to contract, and so their molecules do not have to be slowed down as much by cooling to get them into the solid form. This is just the opposite of what happens in the case of crystalline substances (those which expand as they solidify).

Summary. The heat of fusion of any substance is the number of calories (or B.T.U.) of heat energy required to change 1 gram (or 1 pound) of the substance from a solid to a liquid without producing any change in its temperature.

The heat of fusion of ice = 80 calories per gram
= 144 B.T.U. per pound.

Pressure lowers the melting point of substances which expand on solidifying and raises that of substances which contract on solidifying.

QUESTIONS AND PROBLEMS

A

1. The metal tungsten is used for the filaments of incandescent electric lamps. What is its melting point on the Fahrenheit scale? (See table, p. 226.)

2. Explain how the presence of ice keeps the interior of a refrigerator from becoming warm.

3. Which is the more effective as a cooling agent, 100 lb of ice at 0° C. or 100 lb of water at the same temperature? Why?

4. What is the meaning of the statement that the heat of fusion of mercury is 2.8?

5. If the molecules in solids are closer together than in liquids, why is it that ice will float in water?

6. Why will snow pack into a snowball if the snow is melting, but not if it is much below 0° C.?

7. Five pounds of ice melted in 1 hr in an unopened refrigerator. How many B.T.U. came through the walls of the refrigerator in the hour?

8. Equal weights of hot water and ice are mixed, and the result is water at 0° C. What was the temperature of the hot water?

B

1. (*a*) How many times as much heat is required to melt any piece of ice as to warm the resulting water 1° C.? 1° F.? (*b*) How many foot-pounds of energy are required to do the work of melting 1 lb of ice? (*c*) Where is the energy which disappeared in converting the ice at 0° C. into water at 0° C.?

2. Is it easier to skate on a mild winter day or when it is extremely cold? Why? (See "regelation.")

3. With a thermometer, test the temperatures in the various compartments of your home refrigerator, allowing the thermometer to stay ten minutes in each compartment before taking a reading. Indicate these temperatures in a diagram, with arrows showing the direction of the circulation of the air. Does your refrigerator meet the temperature standards for a good refrigerator?

4. A brass calorimeter (specific heat = .1) weighed 100 g and contained 200 g of water at 45° C. One hundred grams of ice was melted in the hot water with a resulting temperature of 5° C. Calculate the heat of fusion of ice according to the data.

5. A 200-gram iron weight heated to a temperature of 100° C. was placed in a hole bored in a block of ice at temperature 0° C. and allowed to cool to the temperature of the ice. It was found that 27.5 g of ice melted. Calculate the specific heat of iron.

6. (*a*) What is the temperature of a mixture of ice and water? (*b*) What determines whether it is freezing or melting?

7. Just what will occur if 1000 cal enters 20 g of ice at 0° C.?

8. How many grams of ice must be put into 200 g of water at 40° C. to lower the temperature 10° C.?

Evaporation and the Properties of Vapors

Evaporation and temperature. Damp clothes become dry under a hot flatiron but not under a cold one; the sidewalk dries more readily in the sun than in the shade; we put wet objects near a hot stove or radiator when we wish them to dry quickly. All these facts show that evaporation takes place more rapidly at higher temperatures than at low. This is easily explained in terms of the kinetic theory. Since an increase in temperature means an increase in the mean velocity of the molecular motion (see page 189), then, as the temperature increases, a greater number of molecules will manage to get the velocity necessary to carry them away from the attractive forces of their fellow molecules and into the space above the liquid.

Evaporation of solids: sublimation. Since the molecules of solids are also in motion, one can readily see why certain solids like ice, iodine, camphor gum, and moth balls may disappear by evaporation. Ice and snow disappear in winter, even though the temperature may remain below their freezing point. One may detect the odor of moth balls many feet away from an opened trunk. The evaporation of solids may be rendered visible by the following striking experiment:

Place a few crystals of iodine on a watch glass and heat gently with a Bunsen flame. The purple vapor of iodine will appear above the crystals, though none of the liquid is formed.

A great many substances pass at high temperatures from the solid to the gaseous condition without passing through the liquid state. The vaporization of a solid is called *sublimation.*

Saturated vapor. Experience teaches that water left in an open dish wastes away until the dish is completely dry, for as fast as the molecules emerge from the liquid, they are carried away by air currents.

But suppose that the liquid is evaporating into a closed space, such as that shown in Fig. 190. Since the molecules which leave the liquid cannot escape from the space S, it

will become more and more crowded with these molecules. As they move back and forth, an increasing number of them will plunge back again into the liquid. Finally there will be as many returning to the liquid per second as are getting away. The vapor then is said to be *saturated,* for it holds as many molecules per cubic centimeter at the existing temperature as it can.

If the density of the vapor is lessened temporarily by raising the dome *D*, more molecules will escape from the liquid per second than return to it, until the density of the vapor has regained its original value.

Fig. 190. A saturated vapor

If, on the other hand, we lower the dome *D*, the density of the vapor is thereby instantaneously increased and more molecules return to the liquid per second than escape, until by this process the density of the vapor has returned to its saturated value. We learn, then, that *at a given temperature the density of a saturated vapor has a constant value. This value changes with temperature but cannot be affected by changes in volume.*

Pressure of a saturated vapor. Just as a gas exerts a pressure against the walls of the containing vessel by the blows of its moving molecules, so also does a confined vapor. But at any given temperature the density of a saturated vapor can have only a definite value; that is, there can be only a definite number of molecules per cubic centimeter. It follows, therefore, that just as at any temperature the saturated vapor can have only one density, so also it can have only one pressure. This pressure is called *the pressure of the saturated vapor* corresponding to the given temperature.

Set up two Torricellian tubes as in Fig. 191, and with the aid of a curved pipette introduce a drop of ether into the bottom of tube (*a*). This drop will at once rise to the top, and a portion of it will evaporate into the vacuum which exists above the mercury. The pressure of this vapor will push down the mercury column, and the number of centimeters of this depression will be a measure of

the pressure of the vapor. It will be observed that the mercury will fall almost instantly to the lowest level which it will ever reach — a fact which indicates that it takes but a very short time for the condition of saturation to be attained.

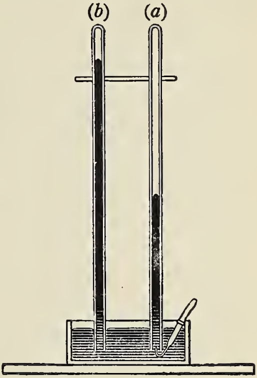


Fig. 191. Vapor pressure of a saturated vapor

The pressure of the saturated ether vapor at the temperature of the room will be found to be as much as 40 centimeters.

Pass a Bunsen flame quickly across the tubes of Fig. 191 near the upper level of the mercury. The vapor pressure will increase rapidly in tube (*a*), as shown by the fall of the mercury column.

The experiment proves that both the pressure and the density of a saturated vapor increase rapidly with the temperature. This was to have been expected from our theory, for increasing the temperature of the liquid increases the mean velocity of its molecules and hence increases the number which attain each second the velocity necessary for escape. How rapidly the density and pressure of saturated water vapor increase with temperature may be seen from the table on the following page. At the boiling temperature (100° C.) this pressure of the saturated vapor becomes equal to the barometric pressure, 760 millimeters of mercury.

The student in the chemistry laboratory, frequently making and collecting gases, such as hydrogen and oxygen, over water, will often use this table. He must know the pressure of these gases in order to find out what volume they would have under standard conditions of pressure and temperature. Knowing the temperature of a gas, he subtracts the corresponding pressure of the saturated water vapor (as given in the table) from the barometer reading to determine the pressure of the gas alone.

Table of Constants of Saturated Water Vapor

[The table shows the pressure P, in millimeters of mercury, and the density D, in grams per cubic centimeter, of water vapor saturated at temperatures $t°$ C.]

t	P	D	t	P	D	t	P	D
− 10°	2.2	.0000023	4°	6.1	.0000064	18°	15.3	.0000152
− 9°	2.3	.0000025	5°	6.5	.0000068	19°	16.3	.0000162
− 8°	2.5	.0000027	6°	7.0	.0000073	20°	17.4	.0000172
− 7°	2.7	.0000029	7°	7.5	.0000077	21°	18.5	.0000182
− 6°	2.9	.0000032	8°	8.0	.0000082	22°	19.6	.0000193
− 5°	3.2	.0000034	9°	8.5	.0000087	23°	20.9	.0000204
− 4°	3.4	.0000037	10°	9.1	.0000093	24°	22.2	.0000216
− 3°	3.7	.0000040	11°	9.8	.0000100	25°	23.5	.0000229
− 2°	3.9	.0000042	12°	10.4	.0000106	26°	25.0	.0000242
− 1°	4.2	.0000045	13°	11.1	.0000112	27°	26.5	.0000256
0°	4.6	.0000049	14°	11.9	.0000120	28°	28.1	.0000270
1°	4.9	.0000052	15°	12.7	.0000128	30°	31.5	.0000301
2°	5.3	.0000056	16°	13.5	.0000135	35°	41.8	.0000393
3°	5.7	.0000060	17°	14.4	.0000144	40°	54.9	.0000509

The influence of air on evaporation. We observed that when ether was inserted into a Torricellian tube the mercury fell *very suddenly* to its final position, showing that in a vacuum the condition of saturation is reached almost instantly. This was to have been expected from the great velocities which we found the molecules of gases and vapors to possess.

Introduce air into tube (*b*) (Fig. 191) until the mercury column stands at a height of from 45 to 55 cm. Measure the height of the mercury column. In order to see what effect the presence of air has upon evaporation, now introduce a drop of ether into the tube. The mercury will not be found to sink instantly to its final level as it did before; but, although it will fall rapidly at first, it will continue to fall slowly for several hours. At the end of a day, if the temperature has remained constant, it will show a depression which indicates a vapor pressure of the ether just as great as that existing in a tube which contains no air.

The experiment leads, then, to the rather remarkable conclusion that *just as much liquid will evaporate into a space which is already full of air as into a vacuum.* The air has no effect except to retard greatly the *rate of evaporation.*

Explanation of the retarding influence of air on evaporation. This retarding influence of air on evaporation is easily explained by the kinetic theory; for, while in a vacuum the molecules which emerge from the surface fly at once to the top of the vessel, when air is present the escaping molecules collide with the air molecules before they have gone any appreciable distance away from the surface (probably less than .00001 centimeter), and only work their way up to the top after an almost infinite number of collisions. Thus, while the space immediately above the liquid may become saturated very quickly, it requires a long time for this condition of saturation to reach the top of the vessel.

Summary. **Liquids evaporate more rapidly as the temperature rises.**

The process by which a solid changes to a gas without passing through the intermediate stage of a liquid is called sublimation.

A saturated vapor is a vapor which is in contact with its liquid and is at its maximum possible density for the existing temperature. Any attempt to increase its density further simply produces condensation.

Both the pressure and the density of a saturated vapor depend on temperature alone and both increase rapidly with rising temperature.

The evaporation of a liquid or a solid is retarded by the presence of gases about its surface, but the final density and pressure of its vapor are independent of the presence of these gases.

QUESTIONS AND PROBLEMS

1. Account for the evaporation of naphthaline moth balls at ordinary room temperatures.

2. If the inside of a barometer tube is wet when it is filled with mercury, will the height of the mercury be the same as in a dry tube? Why?

3. How many grams of water will evaporate at 20° C. into a closed room 18 × 20 × 4 m? (See table, p. 234.)

4. At a temperature of 15° C. what will be the error in the barometric height indicated by a barometer that contains moisture?

5. At 20° C. how great was the error in reading due to the presence of water vapor in Otto von Guericke's barometer?

6. Why are icebergs frequently surrounded with fog?

7. A morning fog generally disappears before noon. Explain the reason for its disappearance.

8. Why will an open narrow-necked bottle containing ether not show as low a temperature as an open shallow dish containing the same amount of ether?

Hygrometry, or the Study of Moisture Conditions in the Atmosphere *

Condensation of water vapor from the air. Were it not for the retarding influence of air upon evaporation we should be obliged to live in an atmosphere which would be always completely saturated with water vapor, for the evaporation from oceans, lakes, and rivers would almost instantly saturate all the regions of the earth. This condition — one in which moist clothes would never dry, and in which all objects would be perpetually soaked in moisture — would be exceedingly uncomfortable, if not altogether unendurable.

But on account of the slowness with which, as the last experiment showed, evaporation into air takes place, the water vapor which always exists in the atmosphere is usually far from saturated, even in the immediate neighborhood of lakes and rivers. Since, however, the amount of vapor which is necessary to produce saturation rapidly decreases with a fall in temperature, if the temperature decreases continually in some unsaturated locality, it is clear that a point must soon be reached at which the amount of vapor already existing in a cubic centimeter of the atmosphere is the amount corresponding to saturation. Then, if the temperature still continues to fall, the vapor must begin to condense. Whether it condenses as dew or cloud or fog or rain will depend upon how and where the cooling takes place.

* It is recommended that this subject be preceded by a laboratory determination of dew point, humidity, etc. See, for example, Experiments 27 and 28 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

The formation of dew and frost. If the cooling is due to the natural radiation of heat from the earth at night after the sun's warmth is withdrawn, the atmosphere itself does not fall in temperature nearly so rapidly as do solid objects on the earth, such as blades of grass, trees, and stones. The layers of air which come into immediate contact with these cooled bodies are themselves cooled, and as they thus reach a temperature at which the amount of moisture which they already contain is in a saturated condition, they begin to deposit this moisture, in the form of dew or frost, upon the cold objects. The drops of moisture which collect on an ice pitcher in summer illustrate perfectly the formation of dew. If condensation takes place upon a surface colder than the freezing temperature, *frost* is formed, as is observed, for instance, on grass and on windowpanes.

The formation of fog. If the cooling at night is so great as not only to bring the grass and trees below the temperature at which the vapor in the air in contact with them is in a state of saturation, but also to lower the whole body of air near the earth below this temperature, then the condensation takes place not only on the solid objects but also on dust particles suspended in the atmosphere. This constitutes a fog.

The formation of clouds, rain, sleet, hail, and snow. When a warm moist current of air near the surface of the earth rises high into a region of less pressure, *it undergoes a marked lowering in temperature on account of its expansion.* (See page 211.) If the resultant temperature due to the expansion is below that at which the amount of moisture already in the air is sufficient to produce saturation, this excessive moisture immediately condenses about floating dust particles and forms a *cloud.* If the cooling is sufficient to free a considerable amount of moisture, the drops become large and fall as *rain.* If this falling rain freezes before it reaches the ground, it is called *sleet.* If the temperature at which condensation begins is below freezing, the condensing moisture forms into *snowflakes.* When the violent air currents which accompany thunderstorms carry the condensed moisture up and down

several times through alternate regions of snow and rain, *hailstones* are formed.

The dew point. *The temperature to which the atmosphere must be cooled in order that condensation of the water vapor within it may begin is called the dew point.* This temperature may be found by partly filling with water a brightly polished vessel of 200 or 300 cubic centimeters capacity and dropping into it little pieces of ice, stirring thoroughly at the same time with a thermometer. The dew point is the temperature indicated by the thermometer at the instant a film of moisture appears upon the polished surface. In winter the dew point may be below freezing, and it will therefore be necessary to add salt to the ice and water in order to make the film appear. The experiment may be performed equally well by bubbling a current of air through ether contained in a polished tube (Fig. 192).

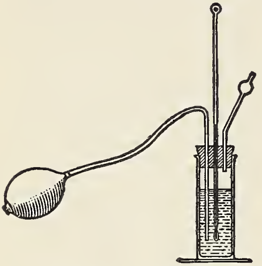


FIG. 192. Apparatus for determining dew point

Humidity of the atmosphere. The amount of moisture actually contained in a unit volume of air is called its absolute humidity. This information is of less value to us, however, than knowing how nearly the air is completely saturated, or its relative humidity. *Relative humidity is defined as the ratio between the amount of moisture per cubic centimeter actually present in the air and the amount which would be present if the air were completely saturated.* This is precisely the same as the ratio between the pressure which the water vapor present in the air exerts and the pressure which it would exert if it were present in sufficient quantity to be in the saturated condition.

[An example will make clear the method of finding the relative humidity. Suppose that the dew point were found to be 15° C. on a day on which the temperature of the room was 25° C. The amount of moisture actually present in the air then saturates it at 15° C. We see from the *P* column in

the table (see page 234) that the pressure of saturated vapor at 15° C. is 12.7 millimeters. This is the pressure exerted by the vapor in the air at the time of our experiment. Running down the table, we see that the moisture required to produce saturation at the temperature of the room, that is, at 25°, would exert a pressure of 23.5 millimeters. Hence at the time of the experiment the air contains 12.7/23.5, or .54, as much water vapor as it might hold. We say, therefore, that the air is 54 per cent saturated, or that the relative humidity is 54 per cent.

Practical value of humidity determinations. From humidity determinations it is possible to get much information regarding the likelihood of rain or frost. Such observations are continually made for this purpose at all meteorological stations. They are also made in greenhouses, to see that the air does not become too dry for the health of the plants, and in hospitals and public buildings and even in private dwellings, in order to insure the maintenance of hygienic living conditions. For the most healthful conditions the relative humidity should be kept at from 45 per cent to 60 per cent, depending on the temperature. Certain manufacturing operations, like knitting and weaving, require a rather high relative humidity to produce a uniform product.

Low relative humidity in the home causes discomfort and colds, and leads to some waste of fuel. The average home heated to 72° F. by steam or hot water is estimated by health authorities to have a relative humidity of 30 per cent, and even as little as 25 per cent with hot-air heating. This is less than the average humidity of extensive desert regions. Higher humidity in the home would diminish the cooling effect due to rapid evaporation of the perspiration from the body, and would make us feel comfortable if a lower temperature were maintained. The chart in Fig. 193 shows what the relative humidity should be, at different room temperatures, for greatest bodily comfort.

Maintaining the proper humidity in the average home during the winter months is extremely difficult, since an

evaporation rate of from 10 to 25 gallons of water per day is necessary to bring it up to 50 per cent. Placing pans of water on the radiators, therefore, is rather ineffective. Probably the simplest rule is not to let the temperature rise above 65° F. or 70° F., because at such a temperature the amount of water vapor necessary for healthful conditions is less.

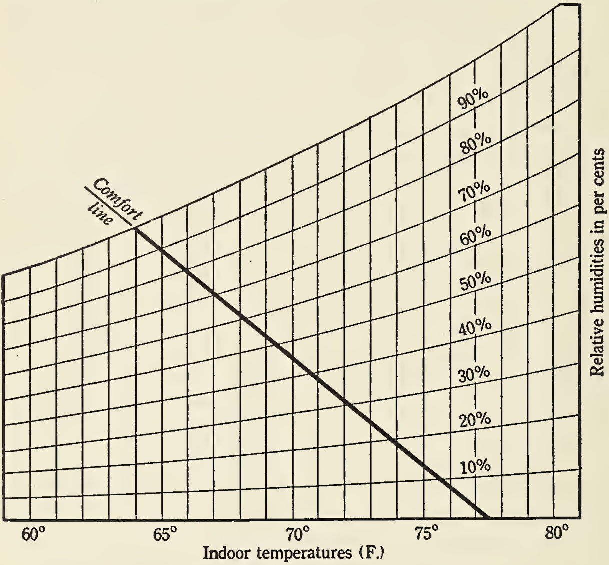


FIG. 193. Comfort chart *

Air-conditioning. Since we spend so much of our life indoors, a great deal of research has been going on to determine the factors making for the most comfortable and hygienic living conditions in our homes, stores, and offices. By observing pulse rate, respiration, and work output, it was found, for instance, that students shut up in an airtight room could

* From Humidity in the Home, *Bulletin I*, Holland Institute of Thermology, Holland, Michigan.

endure relatively high temperatures and humidities with comparative comfort if the air was set in motion by electric fans, but that they suffered great discomfort if the air was still.

All such facts have been combined in the modern science of air-conditioning, which seeks to filter the air and to regulate its temperature, its relative humidity, velocity, etc. in order that we may carry on our indoor activities with the maximum of physical and mental efficiency. Rapid strides have been made in this direction. Already many of our public buildings (such as theaters and department stores) and trains have been equipped with effective air-conditioning apparatus, and progress is being made in furnishing such apparatus for the average small home at a price within reach of the owner's pocketbook.

Cooling effect of evaporation. Fill three shallow dishes, the first with water, the second with alcohol, and the third with ether, the bottles from which these liquids are obtained having stood in the room long enough to acquire its temperature. Allow them to stand for a few minutes; then let three students carefully read as many thermometers, first before their bulbs have been immersed in the respective liquids and then after. In every case the temperature of the liquid in the shallow vessel will be found to be somewhat lower than the temperature of the air, the difference being greatest in the case of ether and least in the case of water.

It appears from these experiments that an evaporating liquid is somewhat cooler than its surroundings, and that the substances that evaporate most readily cool the most.

Another way of establishing the same fact is to place a few drops of each of the above liquids in succession on the bulb of the arrangement shown in Fig. 168 and observe the rise of water in the stem; or, more simply still, to place a few drops of each liquid on the back of the hand and notice that the order in which they evaporate — namely, ether, alcohol, water — is the order of greatest cooling.

In dry, hot climates where ice is not readily obtained drinking water is frequently kept in canvas bags or unglazed earthenware. The slow evaporation of the water from the outside of the porous container keeps the water within quite cool.

In twenty-four hours a healthy person perspires from a pint to a quart, while one who exercises violently may perspire a gallon in that time. The evaporation of this moisture produces a cooling effect on the body and helps it to maintain its uniform temperature of 98.6° F. As we cool off, the pores partly close, thus decreasing the cooling effect.

Explanation of the cooling effect of evaporation. The kinetic theory furnishes a simple explanation of the cooling effect of evaporation. We saw that, in accordance with this theory, evaporation means an escape from the surface of those molecules which have acquired velocities considerably above the average. Losing the most rapidly moving molecules means, of course, that the average velocity of those left behind will be less, just as moving the best students from a schoolroom will leave the average scholarship of the room lower than it was. Since the average molecular velocity is less, it follows that the temperature of the liquid will be lower.

Again, we should expect the amount of cooling to be proportional to the rate at which the liquid is losing molecules. Hence, of the three liquids studied, ether should cool most rapidly, since it evaporates most rapidly. The rate of evaporation of alcohol is intermediate between that of ether and water, and its cooling effect is also intermediate.

Freezing by evaporation. On page 234 it was shown that a liquid will evaporate much more quickly into a vacuum than into a space containing air. Hence, if we place a liquid under the receiver of an air pump and exhaust the air rapidly, we ought to expect a much greater fall in temperature than when the liquid evaporates into air. This conclusion may be strikingly verified as follows:

Fill a thin watch glass with ether and place it upon a drop of cold water, preferably ice water, which rests upon a thin glass plate. Place the whole arrangement underneath the receiver of an air pump and exhaust the air rapidly. After a few minutes of pumping the watch glass will be found frozen to the plate.

It was by evaporating liquid helium in this way and by an additional procedure involving essentially the same prin-

ciple that the very low temperature mentioned on page 195 was reached.

Effect of air currents upon evaporation. Fan rapidly four thermometer bulbs, the first of which is dry, the second wet with water, the third with alcohol, and the fourth with ether, and read their respective temperatures. In all the wet thermometers the fanning will considerably help the cooling, but the dry thermometer will be wholly unaffected.

The reason why fanning thus aids evaporation, and therefore cooling, is that it removes the saturated layers of vapor which are in immediate contact with the liquid and replaces them by unsaturated layers into which new evaporation may at once take place. From the behavior of the dry-bulb thermometer, however, it will be seen that fanning produces cooling only when it can thus hasten evaporation. A dry body at the temperature of the room is not cooled in the slightest degree by blowing a current of air across it.

FIG. 194. The sling psychrometer, a wet-and-dry-bulb hygrometer

The wet-and-dry-bulb hygrometer. The principle of cooling by evaporation finds a very useful application in the measurement of relative humidity with the wet-and-dry-bulb hygrometer, one form of which is shown in Fig. 194. This instrument consists of two thermometers. The bulb of one of them is dry, and that of the other is kept continuously moist by a wick dipping into a vessel of water or by a medicine-dropper. Unless the air is saturated, the wet bulb indicates a lower temperature than the dry one, for the reason that evaporation is continuously taking place from its surface. How much lower it is depends on how rapidly the evaporation proceeds, and this in turn will depend upon the relative humidity of the atmosphere.

Thus in a completely saturated atmosphere no evaporation whatever takes place at the wet bulb, and it consequently indicates the same temperature as the dry one. By comparing the indications of this instrument with those of the dew-point hygrometer (Fig. 192) tables have been constructed which enable one to determine at once from the readings of the two thermometers both the relative humidity and the dew point.* On account of their convenience instruments of this sort are used almost exclusively in practical work. They are not very reliable unless the air is made to circulate about the wet bulb before the reading is taken. In scientific work this is usually accomplished by whirling the instrument around in the air. Opposite page 245 is shown a wet-and-dry-bulb hygrometer the scale of which makes unnecessary the use of all tables: the relative humidity, dew point, and other information are obtained directly from the intersecting curved lines. The form of instrument used by the United States Weather Bureau is shown in Fig. 194.

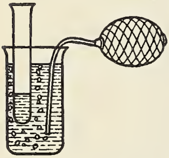


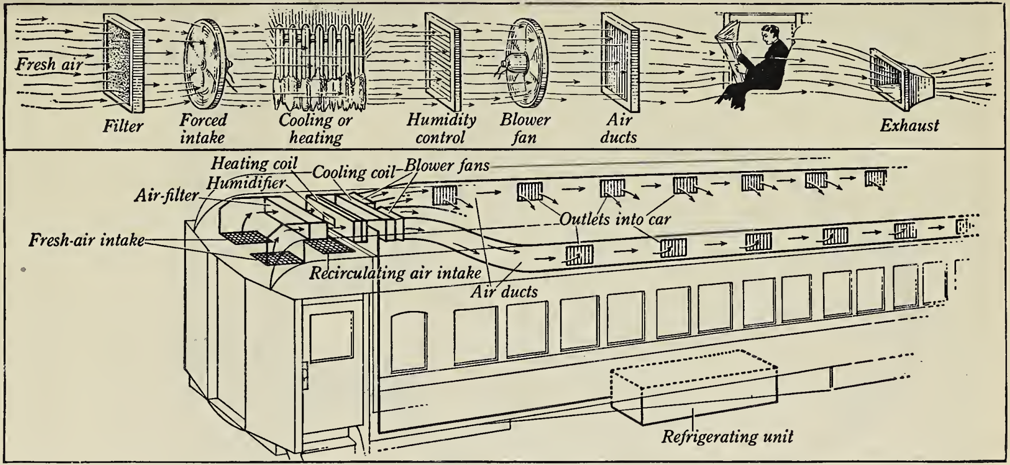
FIG. 195. Freezing water by the evaporation of ether

Effect of increased surface upon evaporation. Dip a small test tube containing a few drops of water into a larger tube or a small glass containing ether, as in Fig. 195, and force a current of air rapidly through the ether in the manner shown. The water within the tube will be frozen in a few minutes, if the aspirator is operated vigorously. The experiment works most successfully if the walls of the test tube are quite thin and the walls of the outer vessel fairly thick. Why?

The effect of passing bubbles through the ether is simply to increase enormously the surface from which evaporation takes place, for the ether molecules which could before escape only at the upper surface can now escape into the air bubbles as well.

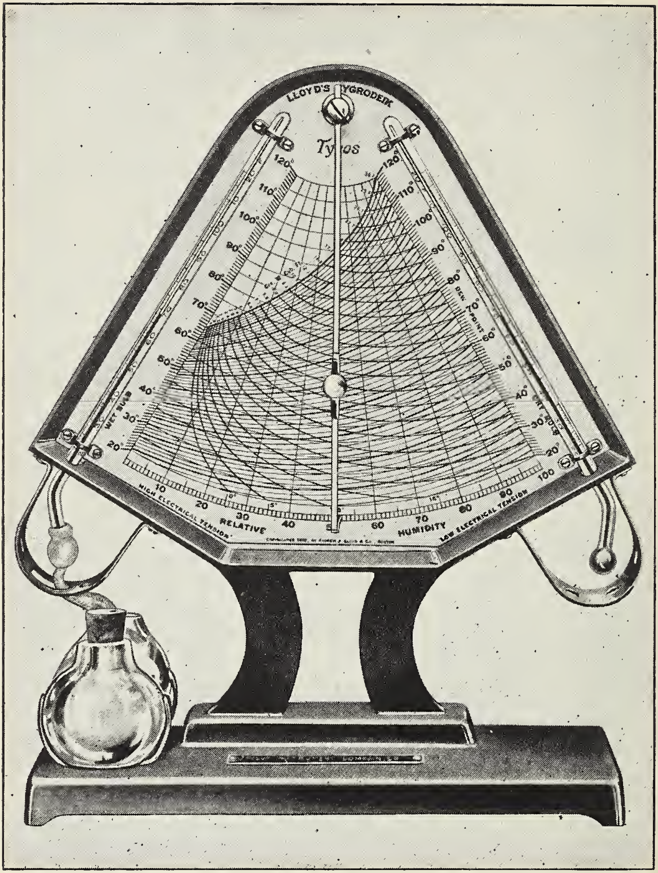
Factors affecting evaporation. The results obtained above may be summarized as follows: The rate of evaporation

* Psychrometric tables may be obtained from the United States Weather Bureau, Washington, D.C.



Air-conditioning of Pullman Cars

The art of air-conditioning involves four elements: control of (1) temperature, (2) humidity, (3) air circulation, and (4) air filtration. The diagrams above show how this control is provided in Pullman cars. The mere removal of dirt, dust, pollen, and germs by the filter (steam-cleaned after each trip) has added greatly to both the comfort and the healthfulness of railroad travel. The refrigerating unit is in one system merely a huge box full of ice; in another system an ammonia refrigerator, in principle like that shown on page 253 and opposite page 254, is used; in a third system (used by the Santa Fe Railroad) the cold is produced by the evaporation of water into a vacuum which is maintained by forcing steam from the engine through a steam-aspirator, in principle like that shown in Fig. 49, p. 65



The Hygrodeik

To determine humidity accurately this instrument should be in a good breeze from a fan or a window

depends (1) on the nature of the evaporating liquid; (2) on the temperature of the evaporating liquid; (3) on the degree of saturation of the space into which the evaporation takes place; (4) on the density of the air or other gas above the evaporating surface; (5) on the rapidity of the circulation of the air above the evaporating surface; (6) on the extent of the exposed surface of the liquid.

Atmospheric moisture and climate. In general, variations in temperature from summer to winter are less near the ocean and the Great Lakes than in inland regions. Inland there is usually less moisture in the air, owing to the absence of great bodies of water, so that the sun's energy passes more freely to warm the surface of the earth in the summer, and this same heat escapes just as readily in wintertime. The moisture in the seaside or the lake air acts like a blanket to hinder the passage of heat.

Near the ocean and the Great Lakes more of the sun's energy is used in summer to warm and vaporize water. Conversely in winter more heat is liberated by the condensation of the moisture of the air into clouds and fogs, and by the slow cooling of the large masses of water. Both these factors tend to keep the temperatures more uniform near large bodies of water than in inland regions.

Summary. **Cooling an unsaturated vapor sufficiently will bring it to a state of saturation; condensation results from further cooling. Depending upon the external conditions, this condensation may appear as dew, frost, fog, clouds, sleet, snow, rain, or hail.**

The dew point is the temperature to which the atmosphere must be cooled in order that condensation of its water vapor may begin.

Relative humidity is the ratio between the amount of moisture per cubic centimeter actually present in the air and the amount which would be present if the air were completely saturated.

The cooling effect of evaporation is due to the evaporation of the more lively molecules; the remaining molecules therefore have a smaller average kinetic energy.

Owing to the presence of greater amounts of atmospheric moisture localities near large bodies of water will have smaller variations in yearly temperatures than inland regions.

QUESTIONS AND PROBLEMS

A

1. At the spout of a boiling teakettle you see first a clear space and then a white cloud. Explain.

2. Why do one's spectacle lenses become coated with mist when one enters a warm house on a cold winter day?

3. Dew will not usually collect on a pitcher of ice water standing in a warm room on a cold winter day. Explain.

4. Explain the formation of frost on the grass.

5. Explain under what conditions frost will form on the inside surface of a window of a house and not on the outside surface.

6. The dew point in a room was found to be 8° C. What was the relative humidity if the temperature of the air was (*a*) 10° C.? (*b*) 20° C.? (*c*) 30° C.? (Consult table, p. 234.)

7. Describe any personal experience which shows that evaporation is a cooling process.

8. If a glass beaker and a porous earthenware vessel are filled with equal amounts of water at the same temperature, in the course of a few minutes a noticeable difference of temperature will exist between the two vessels. (*a*) Which will be the cooler, and why? (*b*) Will the difference in temperature between the two vessels be greater in a dry or in a moist atmosphere?

9. Why is the heat so oppressive on a very damp day in summer?

10. State what factors affecting evaporation are illustrated by the following: (*a*) a wet handkerchief dries faster if spread out; (*b*) clothes dry best on a windy day; (*c*) clothes do not dry rapidly on a cold day; (*d*) clothes dry slowly on moist days. Explain each fact.

11. The sling psychrometer (Fig. 194) is a form of the wet-and-dry-bulb hygrometer. (*a*) Why is it whirled around before readings are taken? (*b*) Why is it best to use distilled water on the wick?

12. From Fig. 193 find out what value of relative humidity would give the greatest bodily comfort at 70° F.

B

1. Would fanning produce a feeling of coolness (*a*) if the face were perfectly dry? (*b*) if the air around us were perfectly saturated? Why?

2. Using a large dictionary, distinguish between a vapor and a gas.

3. At the library look up a recent encyclopedia or magazine article on air-conditioning, and note the physical principles which are involved.

4. Why does sunlight often make the fogs of early morning disappear?

5. What precautions should be taken in the storage of fresh vegetables in an electric refrigerator? Why?

6. Distinguish between absolute humidity and relative humidity.

7. When a room is warmed, what happens (*a*) to its absolute humidity? (*b*) to its relative humidity?

8. Does your school make any attempt to humidify the air? If so, describe the method.

9. Why does heating make moist air dry?

10. (*a*) Why is it necessary to "defrost" an electric refrigerator at regular intervals? (*b*) Where does this coating come from?

11. What weight of water is contained in a room $5 \times 5 \times 3$ m if the relative humidity is 60 per cent and the temperature 20° C.? (See table, p. 234.)

*Boiling**

Heat of vaporization defined. The experiments performed in connection with evaporation led us to the conclusion that, at the free surface of any liquid, molecules frequently acquire velocities sufficiently high to enable them to lift themselves beyond the range of attraction of the molecules of the liquid and to pass off as free gaseous molecules into the space above. They taught us, further, that since it is only such molecules as have unusually high velocities which are able thus to escape, the *average kinetic energy* of the molecules left behind is continuously diminished by this loss from

* It is recommended that this subject be accompanied by a laboratory determination of the boiling point of alcohol by the direct method and by the vapor-pressure method, and that it be followed by an experiment upon the fixed points of a thermometer, the change of boiling point with pressure, and heat of condensation. See, for example, Experiments 18, 19, and 29 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

the liquid of the most rapidly moving molecules, and consequently the temperature of an evaporating liquid constantly falls until the rate at which it is losing heat is equal to the rate at which it receives heat from outside sources. Evaporation, therefore, always takes place at the expense of the heat energy of the liquid. *The number of calories of heat which disappear in the formation of 1 gram of vapor is called the heat of vaporization of the liquid.*

Heat due to condensation. When molecules pass off from the surface of a liquid, they rise against the downward forces exerted upon them by the liquid, and in so doing exchange a part of their kinetic energy for the potential energy of separated molecules in precisely the same way in which a ball thrown upward from the earth exchanges its kinetic energy in rising for the potential energy which is represented by the separation of the ball from the earth. Similarly, just as when the ball falls back it regains in the descent all the kinetic energy lost in the ascent, so when the molecules of the vapor re-enter the liquid they must regain all the kinetic energy which they lost when they passed out of the liquid. We may expect, therefore, that *every gram of steam which condenses will generate in this process the same number of calories as was required to vaporize it.* This is the principle of the steam heating of buildings, by which the heat energy that disappears in converting the water in the boilers into steam is given off again when the steam condenses to water within the radiators.

[Measurement of heat of vaporization. To find accurately the number of calories used up in the vaporization, or released in the condensation, of a gram of water at 100° C., we pass steam rapidly for two or three minutes, from an arrangement like that shown in Fig. 196, into a vessel containing, say, 500 grams of water. We observe the initial and final temperatures and the initial and final weights of the water. If, for example, the gain in weight of the water is 16.4 grams, we know that 16.4 grams of steam has been condensed. If the rise in temperature of the water is from 10° C. to 30° C.,

we know that $500 \times (30 - 10) = 10{,}000$ calories of heat has entered the water. If x represents the number of calories given up by 1 gram of steam in condensing, then the total heat imparted to the water by the condensation of the steam is $16.4\,x$ calories. This condensed steam is at first water at 100° C., which is then cooled to 30° C. In this cooling process it gives up $16.4 \times (100 - 30) = 1148$ calories. Therefore, equating the heat gained by the water to the heat lost by the steam, we have

$$10{,}000 = 16.4\,x + 1148,$$

or $$x = 539 \text{ at } 100° \text{ C.}$$

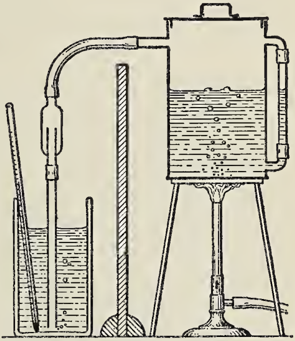


FIG. 196. Heat of vaporization of water

[This is the method usually employed for finding the heat of vaporization. The now accepted value of this constant is 539 calories per gram or 970 B.T.U. per pound.

Boiling temperature defined. If a liquid is heated by means of a flame, it will be found that there is a certain temperature above which it cannot be raised, no matter how rapidly the heat is applied. This is the temperature which exists when bubbles of vapor form at the bottom of the vessel and rise to the surface, growing larger as they rise. This temperature is commonly called the *boiling temperature.*

But a second and more exact definition of the boiling point may be given. It is clear that a bubble of vapor can exist within the liquid only when the pressure exerted by the vapor within the bubble is at least equal to the atmospheric pressure pushing down on the surface of the liquid; for if the pressure within the bubble were less than the outside pressure, the bubble would immediately collapse. Therefore *the boiling point is the temperature at which the pressure of the saturated vapor first becomes equal to the pressure existing outside.*

The following table gives the boiling points of some common substances, that is, the temperatures at which the vapor pressure is equal to atmospheric pressure:

Air	−180° C.	Brine (saturated)	108° C.
Ammonia	−33° C.	Turpentine	160° C.
Ether	35° C.	Mercury	357° C.
Alcohol (grain)	78° C.	Lead	1620° C.
Gasoline	75°–80° C.	Iron	3000° C.

In general a gas in solution will lower the boiling point, but a dissolved solid will raise it. If enough salt be added to water to saturate it, the boiling point will be raised to 108° C.

Some liquids, such as olive oil and melted fats, lard, and butter, have no boiling point at all. The vapor pressure is always less than atmospheric pressure, and so, as they are heated, the temperature continues to rise until the substance either decomposes or carbonizes.

Variation of the boiling point with pressure. Since the boiling point has been defined as the temperature at which the pressure of the saturated vapor is equal to the outside pressure, and since the pressure of a saturated vapor varies rapidly with the temperature (p. 234), it follows that *the boiling point must vary as the outside pressure varies.*

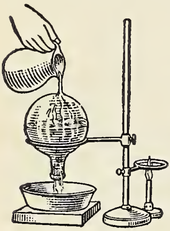


FIG. 197. Lowering the boiling point by diminishing the pressure

Thus, fill a round-bottomed flask half full of water and boil the water. After the boiling has continued for a few minutes, so that the steam has driven out most of the air from the flask, insert a rubber stopper, remove the flask from the flame, and invert it, as shown in Fig. 197. The temperature will fall rapidly below the boiling point; but if cold water is poured over the flask, the water will again begin to boil vigorously, for the cold water, by condensing the steam, lowers the pressure within the flask, and thus enables the water to boil at a temperature lower than 100° C. The boiling will cease, however, as soon as enough vapor is formed to restore the pressure. The operation may be repeated many times without reheating.

At the city of Quito, Ecuador, water boils at 90° C.; on the top of Mont Blanc it boils at 84° C.; and on Pikes Peak, at 89° C. On the other hand, in the boiler of a locomotive on which the gauge records a pressure of 250 pounds per square inch, as is frequently the case, the boiling point of the water is 208° C. (406° F.).

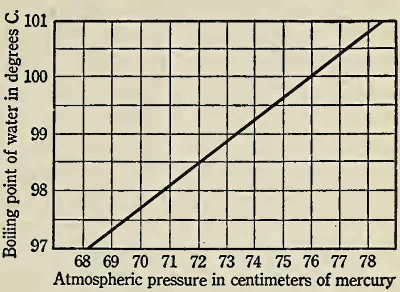


FIG. 198. Effect of pressure on boiling point

In industrial processes liquids which would be harmed by the higher temperatures of ordinary boiling are evaporated under reduced pressure. By this method water is removed from sirup in the manufacture of sugar, and milk is concentrated to form evaporated or condensed milk.

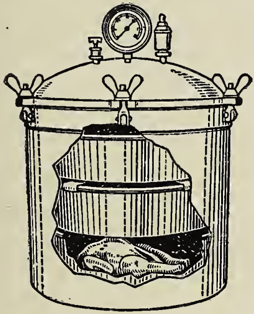


FIG. 199. Pressure cooker

Closed boilers provided with safety valves (see *C*, Fig. 199) and known as *digesters* or *pressure cookers* are used for more rapid cooking in mountainous regions. Indeed, a temperature only a few degrees above 100° C. causes starch grains to burst open much more rapidly than does a temperature of 100° C. Cheap cuts of meat may be made tender in such a cooker. Large digesters are used in extracting gelatin from bones. In the cold-pack method of preserving fruits and vegetables the final sterilizing is often done by placing the jars or cans in closed boilers known as *steam-pressure canners.**

* *Farmers' Bulletin No. 1471*, on steam-pressure canning, may be obtained from the United States Department of Agriculture, Washington, D.C.

Evaporation and boiling. The only essential difference between evaporation and boiling is that the former consists in the passage of molecules into the vaporous condition *from the free surface only*, whereas the latter consists in the passage of the molecules into the vaporous condition both at the free surface and at the surface of bubbles which exist within the body of the liquid. The only reason why vaporization takes place so much more rapidly at the boiling temperature than just below it is that the evaporating *surface* is enormously increased as soon as the bubbles form. The reason why the temperature cannot be raised above the boiling point is that the surface always increases, on account of the bubbles, to just such an extent that the loss of heat because of evaporation is exactly equal to the heat received from the fire.

[**Manufactured ice.** The cooling effect of evaporation is used extensively on a large scale to produce refrigeration for home and industrial use. Artificial ice made by this method is largely superseding natural ice as harvested from lakes and streams in wintertime, and has extended its cooling properties into tropical regions to give new comforts to living. Fig. 200 shows the essential parts of a modern ice plant. A compressor *A* run by an engine forces gaseous ammonia under a pressure of 155 pounds into the condenser coils *B* and there liquefies it. Just as the condensation of steam in a home radiator gives off heat to warm the room, so the liquefying of the ammonia produces heat which must be carried off by the water constantly sprayed over these coils. From the condenser the liquid ammonia is allowed to pass very slowly through the regulating valve *C* into the coils *D* of the evaporator on the left, from which the evaporated ammonia is pumped out so rapidly that the pressure within the coils does not rise above 34 pounds per square inch. This evaporation requires heat. Just as water requires 539 calories of heat per gram to vaporize it, so each gram of liquefied ammonia requires an amount of heat equal to its heat of vaporization (314 calories per gram at 5° F.) to change it into the gaseous state. This heat is taken from its surroundings to cool them

to about 5° F. Around these coils is a strong solution (called a brine) of salt and water. Although cooled by the coils to from 16° to 18° F., the brine does not freeze, owing to the dissolved salt, and so can be made to circulate about cans of water immersed in the brine and thus absorb enough heat to freeze the water. The compressor *A* acts as an exhaust pump on one side and a compression pump on the other.

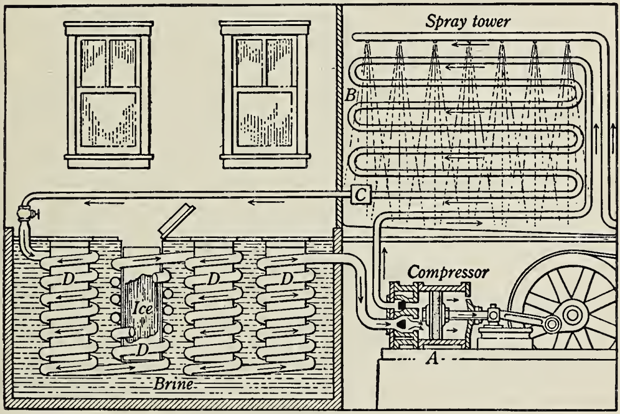


FIG. 200. Manufacture of ice

Large indoor skating rinks are made by laying thousands of feet of iron pipe horizontally, covering the system with water to be frozen, and then circulating through it intensely cold brine.

Artificial cooling of buildings. The artificial cooling of factories, office buildings, and cold-storage rooms is accomplished in a manner exactly similar to that employed in the manufacture of ice. The brine is cooled precisely as described above, and is then pumped through coils placed in the rooms to be cooled. The ammonia is always liquefied in the *condenser* and evaporated in the coils of the *brine tank.* In some systems carbon dioxide is used instead of ammonia,

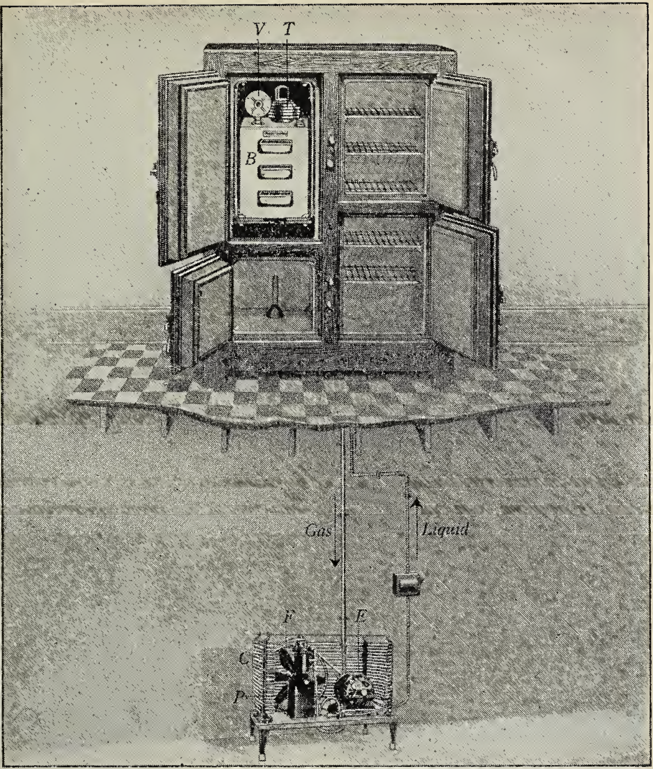
but the principle is in no way altered. Sometimes, too, the brine is dispensed with, and the air of the rooms to be cooled is forced by means of fans directly over the cold coils containing the evaporating ammonia or carbon dioxide. It is often in this way that theaters and hotels are cooled.

Liquefaction of gases. Pressure, cooling, and expansion methods are used in combination to liquefy all the common gases. Even the air we breathe may be caused to assume the liquid form. Liquid air (– 191° C.) is so extremely cold that it produces striking effects on objects immersed in it, because it slows down their molecular action to a marked degree.

Visitors to the Hall of Science at the Century of Progress Exposition in Chicago saw a rubber ball fly into many pieces when an attempt was made to bounce it on the floor after dipping it momentarily in liquid air. Flowers could be crumbled in the hand; mercury froze and was used to drive a nail in a plank. A teakettle of the liquid air when placed on a cake of ice boiled furiously because the ice was about 190° C. hotter than the liquid air. A coil of high-resistance wire when placed in series with a flashlight bulb and battery would allow too little current to flow through the bulb to light it; but when the coil was immersed temporarily in liquid air, the bulb lighted up brilliantly, showing that its resistance was made very much less at the extremely low temperature.

Carbon-dioxide gas also may be liquefied, and even "frozen" to a white solid. It is used for refrigerating purposes, and sold commercially under the trade name "Dry Ice." Owing to its low temperature, – 112° F., and the fact that in changing from a solid to a gas it does not pass through a liquid state as does ordinary ice, it is finding increasing use in the shipping of perishable articles, such as ice cream, in cardboard containers.

Distillation. In *B* (Fig. 201) boil water holding in solution some aniline dye. The vapor of the liquid will pass into the tube *T*, where it will be condensed by the cold water which is kept in continuous circulation through the jacket *J*. The condensed water collected in *P* will be seen to be free from all traces of the color of the aniline.



Household Refrigeration by the Use of Liquid SO_2

The compressing pump P run by the electric motor E liquefies by pressure the gas SO_2 in the compressor coils C, the heat of condensation being partially removed by the fan F. The liquid SO_2 escaping through the expansion valve V into the evaporating coils immersed in the brine tank B rapidly evaporates under the reduced pressures in these coils and maintains the whole tank below the freezing temperature. The thermostat T opens and closes the circuit to the electric motor as needed to maintain constant temperature. The brine tank takes the place of the cake of ice in the old refrigerator. In some systems the brine tank is absent, and the evaporating coils themselves take the place of the ice. (Courtesy of the Kelvinator Corporation)

Quick Freezing of Foods

Quick freezing has been utilized on a commercial scale for food preservation. In ordinary freezing large ice crystals cause the fibrous material to burst, with a detriment, upon thawing, to flavor and color. In quick freezing, however, only small ice crystals form, thus avoiding the rupturing of the fibrous material. When thawed, such foods retain the flavor, color, and appearance of the fresh food. Recently domestic units have been developed for the preservation of food by this method. (Courtesy of Deepfreeze Motor Products Corporation)

We learn, then, that *when solids are dissolved in liquids, the vapor which rises from the solution contains none of the dissolved substance.*

This process, called distillation, is used in many industrial operations. Sometimes it is the pure liquid in P which is desired, as in the manufacture of alcohol, and sometimes the solid which remains in B, as in the manufacture of sugar. In the white-sugar industry it is necessary that the evaporation take place at a low temperature, so that the sugar may not be scorched. Hence the boiler is kept partially exhausted by means of an air pump, thus enabling the solution to boil at considerably reduced temperatures.

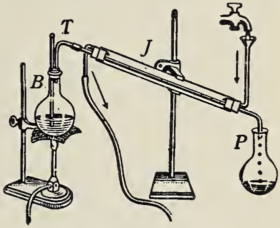


FIG. 201. Distillation

For use in storage batteries ordinary water must be freed from its impurities by distillation, and sea water is distilled on shipboard for drinking purposes.

Fractional distillation. The motorist who uses a mixture of alcohol and water as an "antifreeze" in the radiator of his car may find on a warm day that he has boiled away a great deal of the alcohol. When both the constituents of a solution are volatile, as in the case of a mixture of alcohol and water, the vapor of both will rise from the liquid. But the one which has the lower boiling point—that is, the higher vapor pressure—will predominate. Hence, if we have in B (Fig. 201) a solution consisting of 50 per cent alcohol and 50 per cent water, it is clear that we can obtain in P, by evaporating and condensing, a solution containing a much larger percentage of alcohol. By repeating this operation a number of times we can increase the purity of the alcohol. This process is called *fractional distillation.* The boiling point of the mixture lies between the boiling points of alcohol and water, being higher the greater the percentage of water in the solution.

Crude petroleum, as pumped from the earth, is a mixture

of various liquids having varying boiling points. By boiling, and then condensing the vapors which arise at different temperatures, such products as gasoline, kerosene, naphtha, the various light and heavy lubricating oils, vaseline, and paraffin are separated in turn, as the boiling point of the mixture rises with the passing off of the lighter fractions. This method is used in many other manufacturing processes to produce industrial alcohol, liquors, volatile oils like oil of peppermint, etc.

Cooling by solution. Place a handful of common salt in a small beaker of water at the temperature of the room and stir it with a thermometer. The temperature will fall several degrees. If equal weights of ammonium nitrate and water at 15° C. are mixed, the temperature will fall as low as − 10° C. If the water is nearly at 0° C. when the ammonium nitrate is added, and if the stirring is done with a test tube partly filled with ice-cold water, the water in the tube will be frozen.

These experiments show that heat energy is needed to break up the crystals of a solid in dissolving it, just as heat energy (80 calories per gram) is needed to change ice into water in melting it (p. 223). In each case energy is used up to pull the molecules apart against their natural forces of cohesion. This energy is transformed into the potential energy of separated molecules, and reappears when the substance comes out of solution or when the water is changed back into ice.

Freezing points of solutions. If a solution of one part of common salt to ten of water is placed in a test tube and immersed in a "freezing mixture" of water, ice, and salt, the temperature indicated by a thermometer in the tube will not be zero when ice begins to form, but several degrees below zero. *The ice which does form, however, will be found, like the vapor which rises above the ocean or any other salt solution, to be free from salt,* and this helps to explain why the freezing point of the salt solution is lower than that of pure water. For cooling a substance to its freezing point simply means reducing its temperature, and therefore the mean velocity of its molecules, sufficiently to enable the cohesive forces of the

liquid to pull the molecules together into the crystalline form. Since in the freezing of a salt solution the cohesive forces of the water acting to form the ice are obliged to overcome the attractions of the salt molecules as well as the motions of the water molecules, the motions must be rendered less, that is, the temperature must be made lower, than in the case of pure water in order that crystallization may occur. From this reasoning we should expect that the larger the amount of salt in solution the lower would be the freezing point. This is indeed the case. The lowest freezing point obtainable with common salt in water is $-22°$ C., or $-7.6°$ F. This is the freezing point of a saturated solution.

In general the freezing point of water is lowered whenever anything is dissolved in it. Motorists use this principle when they add alcohol, glycerin, or ethylene glycol (sold under the trade name of "Prestone") to the radiators of their cars in winter. It is important that the substance added have no corrosive effect on any of the parts of the cooling system.

Freezing mixtures. If snow or ice is placed in a vessel of water, the water melts it, and in so doing its temperature is reduced to the freezing point of pure water. Similarly, if ice is placed in salt water, it melts and reduces the temperature of the salt water to the freezing point of the solution. This may be $-1°$, $-2°$, or $-22°$ C., according to the concentration of the solution. Therefore, whether we put the ice in pure water or in salt water, enough of it always melts to reduce the whole mass to the freezing point of the solution, and each gram of ice which melts uses up 80 calories of heat. *The efficiency of a mixture of salt and ice in lowering temperature is therefore due simply to the fact that the freezing point of a salt solution is lower than that of pure water.*

The best proportions for freezing ice cream at home are three parts of snow or finely shaved ice to one part of common salt. If three parts of calcium chloride are mixed with two parts of snow, a temperature of $-55°$ C. may be produced. This is low enough to freeze mercury.

Summary. The heat of vaporization of a liquid is the number of calories of heat absorbed in the formation of 1 gram of vapor or liberated in its condensation. For water at 100° C. it is 539 calories.

The boiling temperature of a liquid is the temperature at which bubbles of its vapor form and rise as such through the body of the liquid, or it is the temperature at which the pressure of the saturated vapor first becomes equal to the pressure on the surface of the liquid.

The boiling point of a liquid varies with the pressure upon it.

Artificial cooling is made possible by utilizing the heat necessary to vaporize liquefied gases.

Distillation is a process of vaporization and condensation by which a liquid is separated from a solid dissolved in it, or by which intermingled liquids having different boiling points are separated.

Cooling by solution of a solid occurs because of the work which has to be done in pulling apart the molecules of the solid crystals. Molecular velocity is lost, that is, heat disappears, in doing this work.

The freezing point of salt water is lower than that of fresh water because the attraction of the salt molecules for the water molecules tends to keep the latter from arranging themselves into crystals of pure ice. At a lower temperature (smaller energy of agitation) the cohesive forces get the mastery and form the pure ice.

A mixture of salt and ice becomes cold because, on account of the low freezing point of salt water (temperature of equilibrium between salt water and ice), the ice begins to melt when brought into contact with the salt and the 80 calories per gram necessary for this melting is taken from the mixture.

QUESTIONS AND PROBLEMS

A

1. After the water in an open vessel first begins to boil, a long time elapses before it is all boiled away. Explain.

2. What is the meaning of the statement that the heat of vaporization of liquid ammonia at 5° C. is 314 cal/g?

3. (*a*) After water has been brought to a boil, will eggs become hard any sooner when the flame is high than when it is low? (*b*) How could you use this answer to help you to save on your gas bill?

4. (*a*) What change in the boiling point of water would be produced by adding some alcohol? (*b*) What disadvantages are there in the use of alcohol as an automobile "antifreeze"?

5. From Fig. 198 find the boiling point of water when the barometer reads 74.5 cm.

6. The hot water which leaves a steam radiator may be as hot as the steam which entered it. How, then, has the room been warmed?

7. Why are burns caused by steam so much more severe than burns caused by hot water of the same temperature?

8. What are the advantages gained by using a pressure cooker?

9. How may we obtain pure drinking water from sea water?

10. Give two reasons why an ocean freezes less easily than a lake.

11. In a certain radiator 2 kg of steam at 100° C. condensed to water in 1 hr, and the water left the radiator at 90° C. How many calories were given to the room during the hour?

12. How many calories are required to convert 10 g of ice at 0° C. into steam at 100° C.?

B

1. Explain why salt is thrown on icy sidewalks on cold winter days.

2. How much would one have to reduce the air pressure on water to make it boil at room temperature (20° C.)? (See table, p. 234.)

3. Explain how a coffee-percolator works.

4. How many grams of steam at 100° C. must be condensed in 1 kg of snow at 0° C. to convert the snow into water at 0° C.?

5. (*a*) If pieces of ice are dropped into water maintained at 0° C., will the ice melt? Why? (*b*) If a saturated brine solution has a temperature of 0° C. and ice is dropped into it, what will happen to the ice? (*c*) to the temperature of the brine solution?

6. (*a*) When the salt in an ice-cream freezer unites with the ice to form brine, about how many calories of heat are used for each gram of ice melted? (*b*) Where does it come from? (*c*) If the freezing point of the salt solution were the same as that of the cream, would the cream freeze?

7. How many kilograms of ice can be formed from water at 0° C. by taking from the water enough heat to vaporize 10 kg of ammonia? (Consider the heat of vaporization of liquid ammonia to be 314 cal/g.)

8. Find the total heat necessary to change 1 g of ice at − 10° C. to steam at 110° C. Plot a graph to represent this change, using calories on the horizontal scale and temperature changes on the vertical scale.

9. (*a*) How many calories are given up by 30 g of steam at 100° C. in condensing and then cooling to 20° C.? (*b*) How much water will this steam raise from 10° C. to 20° C.?

10. (*a*) How many times as much heat is required to convert any weight of water at 100° C. into steam as to warm an equal weight of water 1° C.? 1° F.? (*b*) How many B.T.U. are required to convert 1 lb of water at 212° F. into steam? (*c*) How many foot-pounds of mechanical energy are equivalent to this amount of heat energy?

11. How many B.T.U. are liberated within a radiator when 10 lb of steam condenses there?

12. Why does the distillation of a mixture of alcohol and water always result to some extent in a mixture of alcohol and water?

13. When part of the salt water in a vessel freezes, the ice formed is free from salt. What effect, then, does freezing have on the concentration of the remaining salt solution?

14. A partially concentrated salt solution which has a freezing point of − 5° C. is placed in a room which is kept at − 10° C. Will it all freeze?

Steam Engines

The modern steam engine. Thus far in our study of the transformations of energy we have considered only cases in which mechanical energy was transformed into heat energy. The discovery of a way in which the opposite transformation (from heat energy to mechanical) could be produced brought tremendous changes in the social, economic, and industrial life of the world. The first of the heat engines which changed heat into mechanical energy was the steam engine. The invention of the form now in use is due to James Watt, who at the time of the invention (1768) was an instrument-maker in the University of Glasgow.

The operation of such a machine can best be understood from the ideal diagram shown in Fig. 202. Steam generated in the boiler by the fire passes through the pipe *S* into the

steam chest V, and thence through the passage N into the cylinder C, where its pressure forces the piston P to the left. It will be seen from the figure that as the driving rod R moves toward the left the so-called eccentric rod R', which controls the valve V, moves toward the right. Hence, when the piston has reached the left end of its stroke, the passage N will have been closed, and the passage M will begin to admit steam, thus throwing the pressure from the right to the left

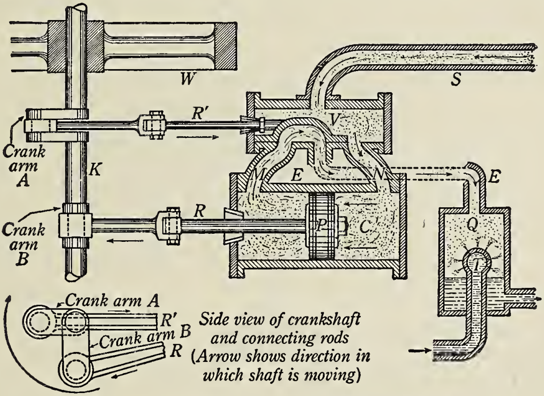


FIG. 202. Ideal diagram of a steam engine

side of the piston, and at the same time putting the right end of the cylinder, which is full of spent steam, into connection with the exhaust pipe E. This operation goes on continuously, the rod R' opening and closing the passages M and N at just the proper moments to keep the piston moving back and forth throughout the length of the cylinder. In the actual engine the slide valve V is so constructed and adjusted that the supply of steam from the boiler is cut off after the piston has made a part of its full stroke, the rest of the stroke being completed under the diminishing expansive pressure of the steam within the cylinder. The shaft carries a heavy flywheel W, the great inertia of which helps to maintain constant speed.

The motion of the shaft is communicated to any desired machinery by means of a belt which passes over the wheel W. Within the boiler the steam is at high pressure and high temperature (p. 251). The steam falls in temperature within the cylinder while doing the work of pushing the piston. *A steam engine is a mechanical device which accomplishes useful work by transforming heat energy into mechanical energy.*

Condensing and noncondensing engines. In most stationary engines the exhaust E leads to a condenser which consists of a chamber Q, into which plays a jet of cold water T, and in which a partial vacuum is maintained by means of an air pump. In the best engines the pressure within Q is not more than from 3 to 5 centimeters of mercury, that is, not more than a pound to the square inch. Hence the condenser reduces the back pressure against that end of the piston which is open to the atmosphere from 15 pounds down to 1 pound per square inch and thus increases the effective pressure which the steam on the other side of the piston can exert.

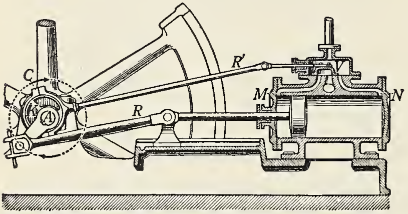


FIG. 203. The eccentric

[The eccentric. In practice the valve rod R' is not attached as in the ideal engine indicated in Fig. 202, but motion is communicated to it by a so-called *eccentric*. This consists of a circular disk K (Fig. 203) rigidly attached to the axle but so set that its center does not coincide with the center of the axle A. The disk K rotates inside the collar C and thus communicates to the eccentric rod R' a back-and-forth motion which operates the valve V in such a way as to admit steam alternately through M and N at the proper time.

[The boiler. When an engine is at work, steam is being removed very rapidly from the boiler; for example, a railway

locomotive consumes from 3 to 6 tons of water per hour. It is therefore necessary to have the fire in contact with as large a surface as possible. In the tubular boiler this end is accomplished by causing the flames to pass through a large number of metal tubes immersed in water. The arrangement of the furnace and the boiler may be seen from the diagram of a locomotive shown in Fig. 204. (See early and modern types opposite page 170.)

[By means of an endless-chain grate, called an automatic stoker, modern power plants feed the coal to the boiler a little

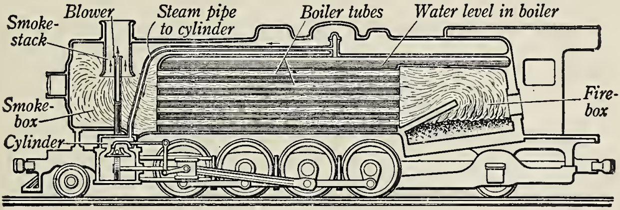


FIG. 204. Diagram of a locomotive

at a time on the underside of the fire. Thus the top of the fire is always burning freely to give maximum combustion and a minimum of smoke.

[**The draft.** In order to force the flames through the tubes of the boiler a powerful draft is required. In locomotives this is obtained by running the exhaust steam from the cylinder (Fig. 204) into the smokestack through the blower. The strong current through the blower draws with it a portion of the air from the smokebox, thus producing within the smokebox a partial vacuum into which a powerful draft rushes from the furnace through the tubes. About 20 pounds of air is required to burn 1 pound of coal. The coal consumption of an ordinary locomotive is from one-fourth ton to one ton per hour. A few modern locomotives have substituted oil for coal.

[In stationary engines a draft is obtained by making the smokestack very high. Since in this case the pressure which

is forcing the air through the furnace is equal to the difference in the weights of columns of air of unit cross section inside and outside the chimney, it is evident that this pressure will be greater the greater the height of the smokestack. This is the reason for the immense heights given to chimneys in large power plants.

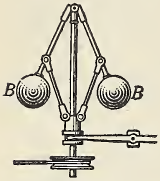


FIG. 205. The governor

The governor. Fig. 205 shows an ingenious device of Watt's, called a *governor*, for automatically regulating the speed with which a stationary engine runs. If it runs too fast, the heavy rotating balls B move apart and upward (why?) and in so doing operate a valve which reduces the speed by partially shutting off the supply of steam from the cylinder.

Compound engines. In an engine which has but a single cylinder the full force of the steam has not been spent when the cylinder is opened to the exhaust. In the compound engine this partially spent steam is allowed to pass into a second cylinder of larger area than the first, where more of its energy is taken from it. The most efficient of the modern engines have three and sometimes four cylinders of this sort, and accordingly they are called *triple-expansion* or *quadruple-expansion engines*. Fig. 206 shows the relation between any two successive cylinders of a cross-compound engine. By automatic devices not differing in principle from the eccentric, valves C_1, D_2, and E_2 open simultaneously and thus permit steam from the boiler to enter the small cylinder A, while the partially spent steam in the other

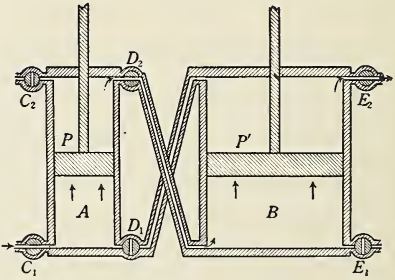


FIG. 206. Cross-compound engine cylinders

end of the same cylinder passes through D_2 into B, and the more fully exhausted steam in the upper end of B passes out through E_2. Near the upper end of the stroke of the pistons P and P', C_1, D_2, and E_2 automatically close, while C_2, D_1, and E_1 simultaneously open and thus reverse the direction of motion of both pistons. These pistons are attached to the same shaft.

Efficiency of a steam engine. We have seen that it is possible to transform completely a given amount of mechanical energy into heat energy. This is done whenever a moving body is brought to rest by means of a frictional resistance. But the inverse operation, namely, that of transforming heat energy into mechanical energy, differs from this in that it is only a comparatively small fraction of the heat developed by combustion which can be transformed into work. For it is not difficult to see that in every steam engine at least a part of the heat must of necessity pass over with the exhaust steam into the condenser or out into the atmosphere. This loss is so great that even in an ideal steam engine not more than about a third of the heat of combustion could be transformed into work. In some modern steam-generator plants in which all heat losses are minimized, an amazing running efficiency is maintained. Actually in the world's most efficient stationary engine running at a steam pressure of 1400 pounds per square inch 33 per cent of the heat value of the fuel is converted into electrical energy. The best steam locomotives utilize at most not more than 13 per cent. *The efficiency of a heat engine is defined as the ratio between the heat utilized, or transformed into work, and the total heat expended.* The efficiency of the best steam locomotive is, therefore, less than half of the attainable limit.

[**The steam turbine.** The steam turbine (see opposite page 266) represents the latest development of the steam engine. In principle it is very much like the common windmill, the chief difference being that it is steam instead of air which is driven at a high velocity against a series of blades arranged radially about the circumference of the wheel that is set into

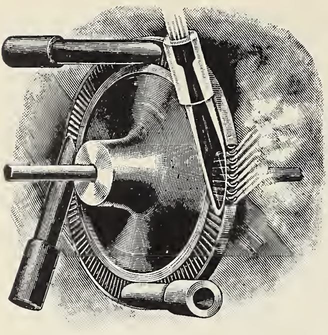


FIG. 207. The principle of the steam turbine

rotation. The steam, however, unlike the wind, is always directed by nozzles at the angle of greatest efficiency against the blades (Fig. 207). Furthermore, since the energy of the steam is far from spent after it has passed through one set of blades (such as that shown in Fig. 207), it is in practice always passed through a whole series of such sets (Fig. 208), every alternate row of which is rigidly attached to the rotating shaft. The intermediate rows are fastened to the immovable outer jacket of the engine and only serve as guides to redirect the steam at the most favorable angle against the next row of movable blades. In this way the steam is kept alternately bounding from fixed to movable blades until its energy is expended. There are often as many as sixteen rows of blades. The transformation of heat energy into mechanical energy is due largely to changes in momentum of the steam as it passes through the blade channels, whereas in the reciprocating steam engine it occurs through a statical pressure of the steam against the piston.

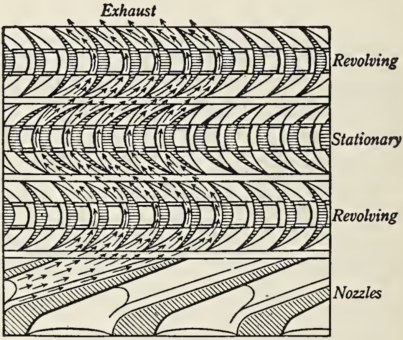
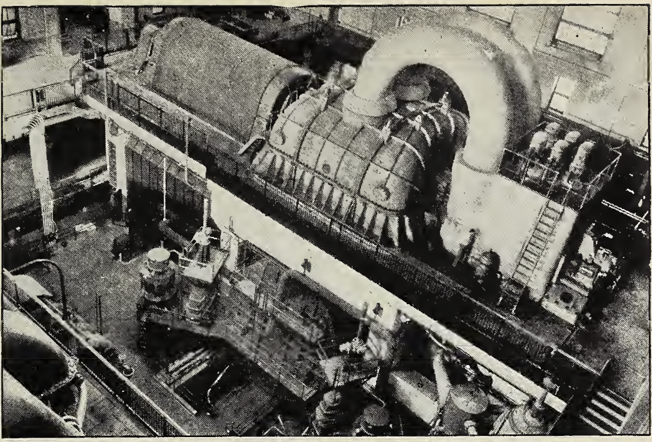
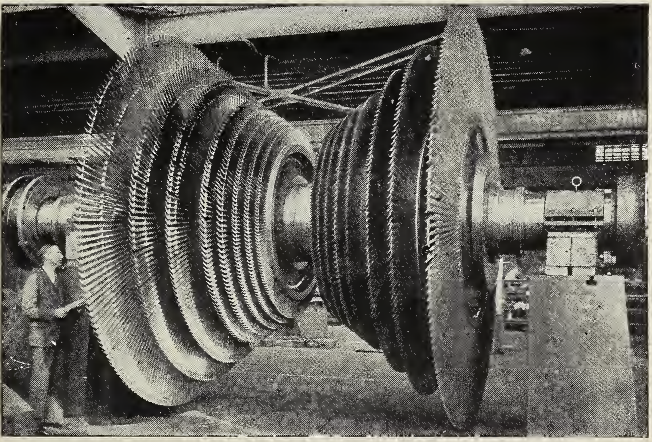


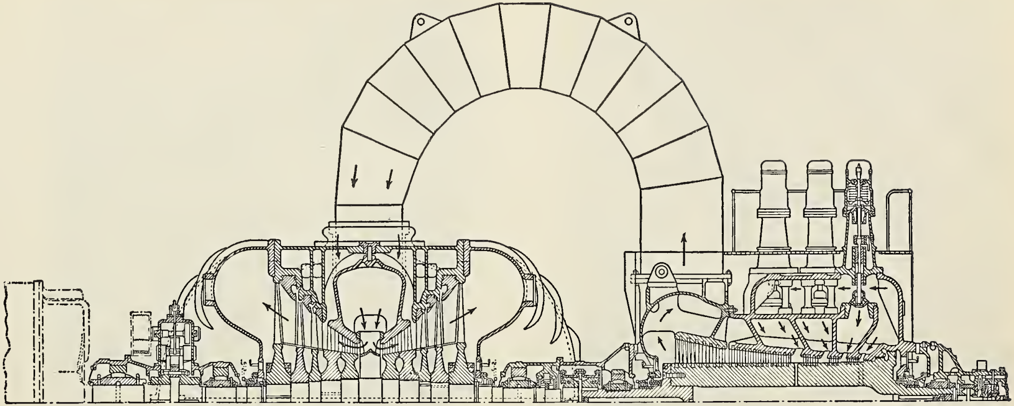
FIG. 208. Cross section through blades and nozzles of steam turbine



Largest Single-Shaft Steam Engine Yet Built, 165,000 Kilowatts
Courtesy of the Westinghouse Electric Company



Huge, Many-bladed Rotor Used on the Low-Pressure Side of the Engine Above. (See the next page)



Cross Section of the Upper Half of a 165,000-Kilowatt Steam Turbine

The path of the steam is shown, first through the high-pressure stage on the right (see arrows) and then over through the large central pipe to the low-pressure stage on the left. Here, as indicated by the arrows, the steam spreads out in both directions and then passes out through the series of fixed blades, shown above, and of movable blades, or buckets, of ever-expanding size, shown in the lower figure of the preceding page. These movable buckets fit in between the fixed blades, as is indicated on page 266. By the time that the steam reaches the condenser, it has given up practically all its energy to the rotating shaft and is ready to condense in a "vacuum chamber" which is held at a pressure of "29 inches of vacuum." (Courtesy of the Westinghouse Electric Company)

[For large-power purposes the turbine is at present coming rapidly into use. For the same power output it occupies less than one tenth the floor space, and its efficiency is slightly higher than that of the best high-power reciprocating engine. Only at maximum speed, however, does it work most efficiently, and it cannot be reversed. The highest speeds attained by vessels at sea, namely, about 40 miles per hour, have been made with the aid of steam turbines. The French liner *Normandie* (1028 feet long, 119 feet wide, total displacement 79,000 tons, top speed 35 knots) is driven by four steam turbines having a total shaft horsepower of 160,000. For flexibility the turbines are not connected directly to the propellers but to four huge alternators (alternating-current dynamos). These furnish the current to drive four motors which are directly connected to four propellers. On its maiden voyage in 1935 the *Normandie* crossed the Atlantic in the new record time of four days and three hours.

Summary. **The invention and perfection of the steam engine and its use to do man's work brought to mankind a new era of comfort and civilization, changing his economic and social habits completely.**

A steam engine transforms heat energy into mechanical energy through the use of superheated steam, which cools during the act of producing motion or doing work.

A condensing engine increases the effective boiler pressure about 14 pounds per square inch.

A compound engine is more efficient than one having a single cylinder because in the former a larger percentage of the total expansive force of the steam can be utilized before final exhaust.

Turbine engines occupy relatively small floor space, are very free from vibrations, and utilize most fully the expansive power of the steam.

QUESTIONS AND PROBLEMS

A

1. How does the temperature of the steam within a locomotive boiler compare with its temperature at the moment of exhaust? Explain.

2. On the drive wheels of locomotives there is a mass of iron opposite the point of attachment of the drive shaft. Why is this necessary?

3. Why does not the water in a locomotive boil at 100° C.?

4. When the steam gauge of a locomotive records 250 lb/in.^{2}, the steam is at a temperature of 406° F. Explain how the steam produces this great pressure.

5. What pull does a 1000 H.P. locomotive exert when it is running at 25 mi/hr and exerting its full horsepower?

6. (*a*) If the average pressure in the cylinder of a steam engine is 10 kg/cm^2, and the area of the piston is 427 cm^2, how much work is done by the piston in a stroke of length 50 cm? (*b*) How many calories did the steam lose in this operation?

B

1. What are the advantages (*a*) of the turbine? (*b*) of the reciprocating steam engine over the turbine? (*c*) of compound engines? (*d*) of condensing engines?

2. In a steam engine what is the function of the (*a*) flywheel? (*b*) slide valve? (*c*) condenser? (*d*) eccentric? (*e*) governor?

3. In an encyclopedia or other source of information find out what advantage the Corliss valve has over the slide valve as described on page 261.

4. Find the horsepower of a steam engine whose average pressure is 150 lb/in.^{2}, the diameter of the piston 14 in., the stroke 24 in., and the speed 500 revolutions per minute. (Remember that there are two power strokes to each revolution.)

5. The average locomotive has an efficiency of about 9 per cent. What horsepower does it develop when it is consuming 1 t of coal per hour? (Assume that 1 lb of coal gives 14,000 B.T.U.)

Internal-Combustion Engines

Principle of the internal-combustion engine. Push two iron or steel wires through a cork stopper and bring their ends *s* near together ($\frac{1}{32}$ in. will do) (Fig. 209). By displacement of water introduce into the inverted bottle enough illuminating gas to fill it about one fifth, allowing the remainder of the water to run out, or with an atomizer spray into the bottle a small amount of benzine or gasoline

(the amount to use can be determined by trial); insert the stopper, and bring the tips of the heavily insulated wires leading from an induction coil to the under side of the wires *a, b*. A spark will pass at *s*; and, if the mixture is not too "lean" or too "rich," a violent explosion will occur, throwing the stopper as high as the ceiling. (*A heavy round bottle must be used for safety. Wrap it well in wire gauze.*)

In distinction to the steam engine, which might be called an "external-combustion" engine because the fuel is burned *outside* the cylinders to form steam as the energy-carrying agent, the gas engine is called an internal-combustion engine, because the fuel is burned directly behind the pistons *in* the combustion chambers. As a result of the combustion, gases are formed whose normal volume is many hundreds of times the original volume of the gasoline. The expansive force of these products of combustion pushes the piston through its stroke.

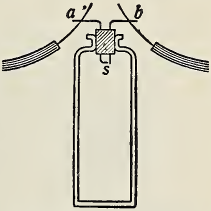


FIG. 209. A mixture of gasoline vapor and air will explode

Within the last two decades gas engines have become quite as important a factor in modern life as steam engines. (See opposite pages 117, 138, and 270.) Such engines are driven by properly timed ignitions of a mixture of gas, or gasoline vapor, and air occurring within the combustion chamber.

Fig. 210 is a diagram illustrating the four stages into which it is convenient to divide the complete cycle of operations which goes on within each cylinder of such an engine. Suppose that the engine has already been set in motion. As the piston *P* moves down in the first stroke (see (*a*)) the intake valve *D* is forced open by a cam on the rotating camshaft (see opposite page 270) and a mixture of gas and air is drawn into the cylinder through *D*. As the piston rises (see (*b*)), valve *D* is forced shut by a spiral spring and the mixture of gas and air is compressed into a small space in the upper end of the cylinder. An electric spark ignites the mixture, and the force of the expansion drives the piston down (see

(*c*)). At the beginning of the return stroke (see (*d*)) the exhaust valve *E* is forced open, and as the piston moves up, the spent gaseous products of combustion are forced out of the cylinder. The initial condition is thus restored and the cycle represented by the four strokes begins over again.

By combining on the upstroke both the inflow of gas and its compression, and on the downstroke the combustion and the exhaust, it is possible in another form, called the two-

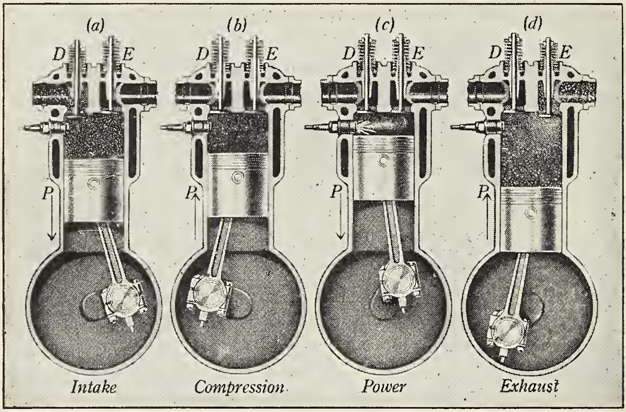
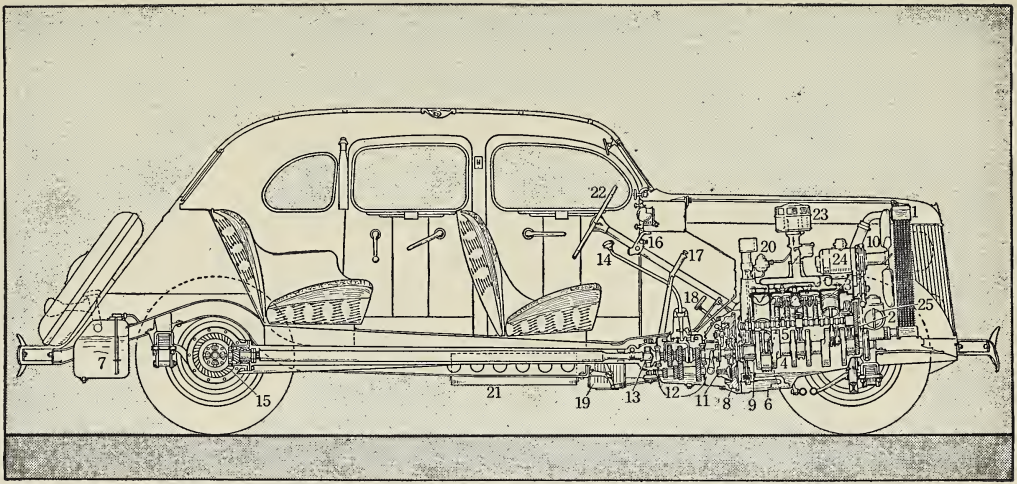


FIG. 210. Principle of the gas engine

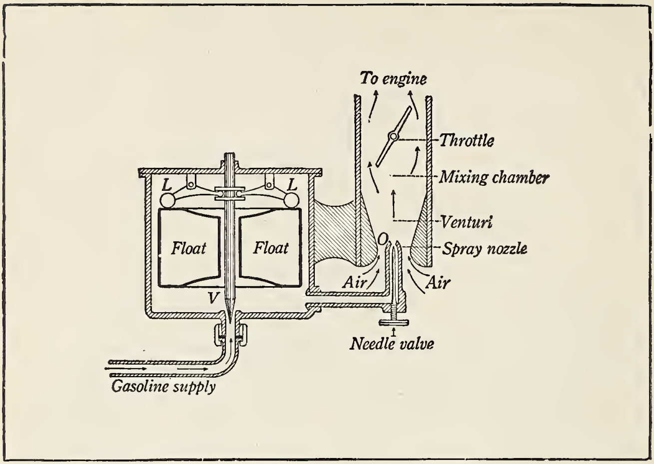
cycle engine, to get a power impulse for each revolution. Such a type is used for outboard motors, where lightness is desirable. It requires more fuel per horsepower, however, than the more common four-cycle form, and is more "temperamental" in starting.

Since the single-cylinder engine of the four-cycle form receives energy from the expanding gas only on the third stroke, the flywheel is always made very heavy, so that the energy stored up in it in the third stroke may keep the machine running with little loss of speed during the other three strokes of the cycle.

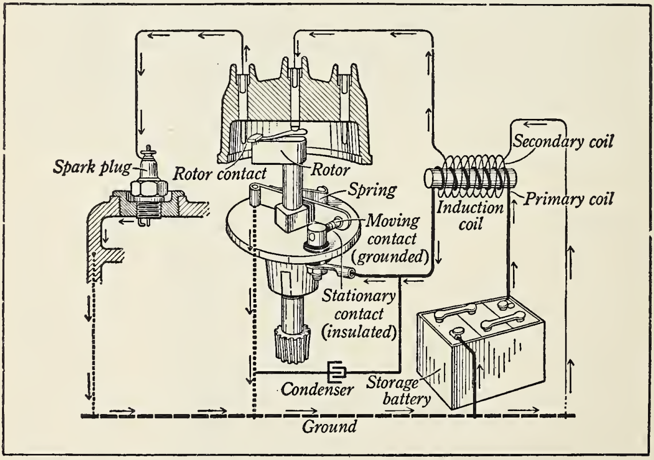


Section of a Modern Automobile, Showing the Principal Mechanical Parts

The numbered parts in this diagram are 1, radiator; 2, timing gears to operate valves in proper relation to position of pistons; 3, pistons; 4, crankshaft; 5, valve stems and push rods operated by cams on the camshaft; 6, oil reservoir; 7, gasoline tank; 8, flywheel; 9, main rear bearing; 10, cooling fan; 11, clutch for connecting the crankshaft of the engine to the transmission; 12, transmission; 13, universal joint; 14, gearshift lever; 15, main driving gear and pinion; 16, electric control switch; 17, emergency-brake lever; 18, service-brake foot lever; 19, storage battery; 20, fuel pump; 21, muffler; 22, steering wheel; 23, air-cleaner; 24, generator; 25, distributor



The Carburetor



A Battery Ignition System Using a Nonvibrating Induction Coil, a Breaker, and a Rotating Distributor

For greater smoothness the individual cylinders are grouped together in sets of four, six, eight, or twelve, operating on a single crankshaft. Each cylinder may then be rather small, and each impulse relatively weak, but since these impulses tend to overlap as the number of cylinders is increased, it is possible to get a smooth uniform torque (turning effect) approaching that of an electric motor. The smoothness of operation is increased by the use of gasoline containing lead compounds which tend to decrease the rapidity of combustion. This gives a smooth push to the piston rather than an explosive, hammerlike blow.

The efficiency of the gas engine is sometimes as high as 32 per cent, practically the same as that of the best steam engines. Furthermore, it is free from smoke, is very compact, and may be started at a moment's notice. On the other hand, the gas engine has little power at low speeds, cannot be reversed, needs gears to make it most efficient at all speeds, cannot be started by itself, and its fuel cost is relatively high. Automobiles are run by gasoline engines, chiefly, because the lightness of the engine and of the fuel to be carried are here considerations of great importance.

It has been the development of the light and efficient gas engine that has made possible man's recent conquest of the air through the use of the airplane and the airship.

The automobile. The plate opposite page 270 shows the principal mechanical features of the automobile in their relation to one another. It will be seen that the cylinders of the engine are surrounded by water jackets which form part of a circulating system. Unless some means were provided for cooling, the engine would become so overheated that the gas would ignite before the pistons had reached their proper point, with resultant "knocking" of the engine; or the pistons would stick fast, owing to excessive expansion. The extra heat of the engine is absorbed by the water, which is pumped to the radiator, where the heat is carried off by the air currents produced by a revolving fan (*10*). A few engines are *air-cooled* by forcing a stream of air over their

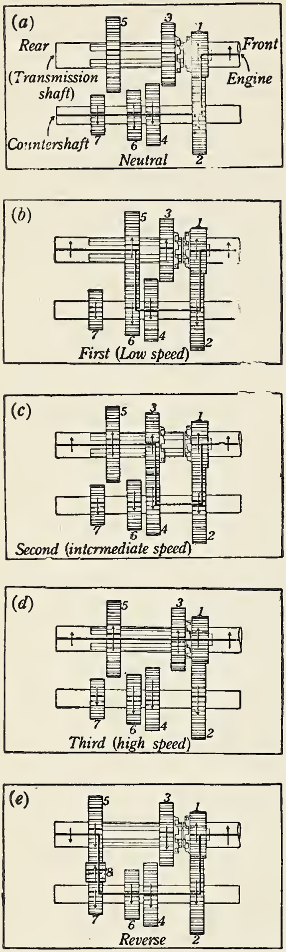


FIG. 211. Automobile transmission (simplified)

outer surfaces, which have cooling fins to give a maximum surface for the radiation of heat. This type of cooling is used in motorcycles, in a few automobiles, and on most airplane engines. The power of the automobile engine is transmitted to the rear axle through the clutch (*11*), the transmission (*12*), and the differential gearing.

The clutch and the transmission. Since a gas engine develops its power by a series of combustions within the cylinders, it is clear that it cannot start with a load, as does the steam engine. In starting an automobile it is necessary first that the engine acquire a reasonable speed and that the power be applied gradually to the rear axle by the use of a friction clutch (*11*); otherwise the engine will stall. In the *single-disk* clutch there is one disk attached to the clutch shaft; the clutch shaft transmits the power from the engine to the transmission by a spring pressure which forces the disk to the face of the flywheel. When the clutch is engaged, two plates and the driving disk are held together by a powerful spring strong enough to prevent their slipping. The

driver throws out the clutch (disconnects the engine) by depressing a lever with his foot (Fig. 142). In the *multiple-disk* clutch the bearing surfaces are two series of disks, one revolving with the flywheel, the other with the clutch shaft.

[The amount of work done by a gas engine in a minute depends upon the work done by each combustion multiplied by the number of ignitions per minute. Therefore it can develop its full power only while revolving rapidly. In hill

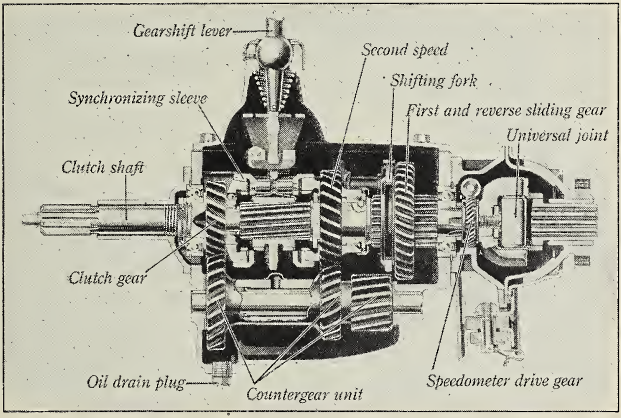


FIG. 212. Modern transmission, showing helical gears *

climbing, for example, the speed of the engine must be great while that of the car is comparatively small. To meet this requirement a system of reduction gears called the transmission (*12* and Fig. 211) is used to make the number of revolutions of the driving shaft less than that of the crankshaft (*4*) of the engine. In Fig. 211 (*a*) the gears are in *neutral*, gears *1* and *2* being always in mesh. By use of the gearshift lever (*14*) gears *3* and *5* (Fig. 211) are made to slide upon a square shaft. Before shifting the gears the clutch is released to disconnect the power of the motor from the

* Courtesy of Buick Motor Company.

drive shaft. In older-model cars the driver had to be very careful not to shift while the gears to be meshed were revolving at different speeds. Most modern cars are equipped with so-called synchromesh transmissions. In these devices there are little clutches on each pair of gears which automatically bring them to the same speed of revolution before they mesh. In this way the clashing of gears is avoided. Fig. 211 (*b*) shows the low-speed connection. In shifting to second speed (Fig. 211 (*c*)) the clutch is released, gear *5* is thrown into neutral, and finally gear *3* is meshed with *4*, after which the clutch is allowed to grip. In going to high speed (Fig. 211 (*d*)) gear *3* is shifted through neutral to engagement with gear *1*. This connects the crankshaft of the engine directly to the drive shaft so that the two revolve at the same speed. For the reverse (Fig. 211 (*e*)) gear *8* simultaneously engages *5* and *7*. Placing a third gear wheel between *5* and *7* obviously reverses the direction of rotation of the drive shaft.

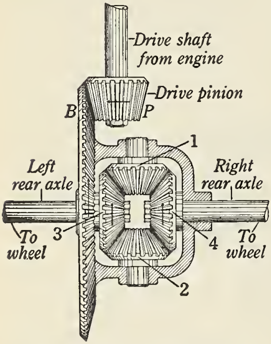


FIG. 213. The differential

[Fig. 211 is drawn in simplest form to show the essential operation of the transmission. Modern practice, however, uses the form shown in Fig. 212. Notice the helical gears, designed for quiet operation, and the synchromesh, affording easy shifting of gears.

[**The differential.** An automobile is driven by power applied to the rear axle. This requires the axle to be in two parts with a *differential* between, so that in turning corners the outer wheel may revolve faster than the inner. It will be seen from the large drawing opposite page 270, and from Fig. 213, that the pinion attached to the drive shaft rotates the main bevel gear *B*, to which are attached the differential gears *1* and *2*. The left axle is directly connected to gear *3*,

and only indirectly connected to the main bevel gear *B* through gears *1* and *2*. In running straight both rear wheels revolve at the same rate; therefore, while gears *3* and *4* and the main bevel gear are revolving at the same speed, they carry around with them pinions *1* and *2*, which are now, however, not revolving on their bearings. When the car is turning a corner, gears *3* and *4* are turning at *different* rates; hence pinions *1* and *2* not only are carried around by the main bevel gear but at the same time are revolved on their bearings.

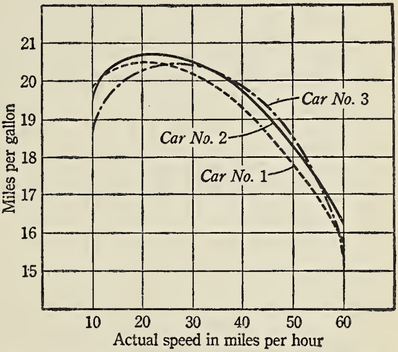


FIG. 214. Fuel test on three popular, small 1935 automobiles. Gasoline consumption increases markedly at higher speeds *

[The carburetor. The carburetor is a device for atomizing liquid gasoline, kerosene, etc. and mixing it with air in proper proportions for complete combustion. The simple principle of carburetion is shown in the upper diagram opposite page 271. Liquid gasoline comes through the supply pipe and enters the float chamber through the valve *V*. By acting on the levers *L* the float closes the valve *V* when the gasoline reaches a certain level. From the float chamber the gasoline passes to the nozzle *O*. While the engine is running, the downward movement of the pistons in stroke (*a*) (Fig. 210) causes air to move swiftly past the nozzle into the region called the *venturi*, where the jet of gasoline is emerging from *O*. The spray of fuel thus formed intermingles with air in the mixing chamber and passes by the throttle to the engine.

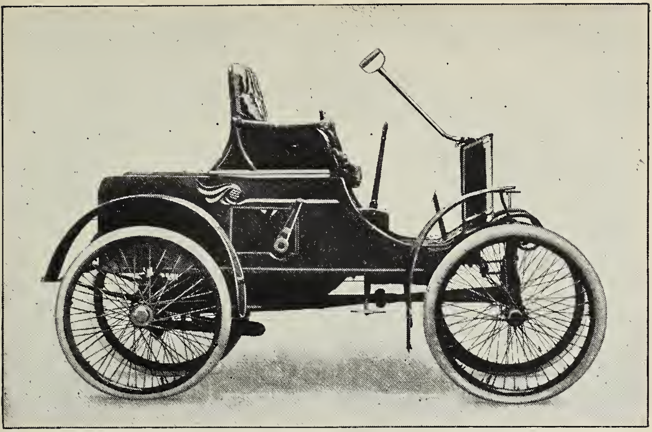
* Reprinted by special permission from *Consumers' Research Bulletin*, May, 1935, issued by Consumers' Research, Inc., Washington, New Jersey.

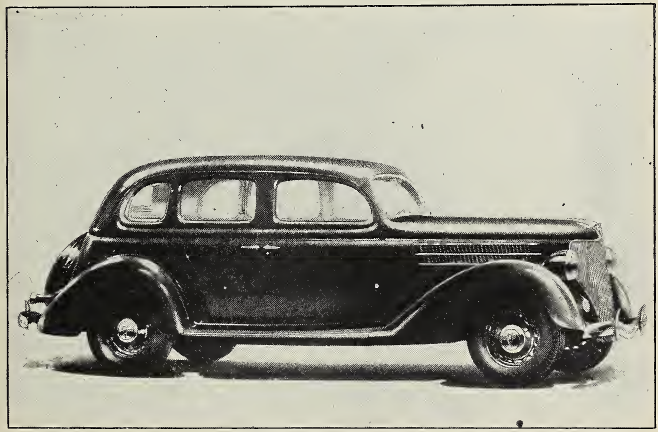
[**The ignition.** The lower diagram opposite page 271 illustrates the principle of battery ignition which is in extensive use on automobiles. A low-tension current, usually of from 6 to 8 volts, passes from a storage battery through the primary coil of an induction coil, through a moving contact, and thence through the framework of the car to the battery. While the engine is running, a rotor (see diagram) makes successive contacts with the 4 or more terminals connected to the 4 or more spark plugs. The mechanism is so timed, or adjusted, that at the right instant for the mixture to be ignited, and while the rotor is touching the proper rotor contact, the cam separates the grounded moving contact from the stationary insulated contact, thus breaking the primary circuit to produce a momentary high-tension current in the secondary of the induction coil. In this way a spark is produced at the terminals of each spark plug, as shown in Fig. 210 (*c*). As many rotor contacts and spark plugs are employed as there are cylinders in the engine.

[Since the power stroke of the piston occurs but once in two revolutions of the crankshaft, it is necessary that the crankshaft revolve twice while the camshaft revolves but once. This, as shown in *2* of the diagram opposite page 270, is accomplished by having the crankshaft geared to the camshaft in a gear ratio of 2 to 1.

[The mixture requires a very short but measurable time for combustion; hence the full force of the combustion occurs a short time *after* the spark ignites the mixture. Therefore, at high speed the spark should occur a little earlier with reference to the position of the piston than at low speed. The spark may be *advanced* or *retarded* manually (by hand) by slightly rotating the plate to which the moving and stationary contacts are attached, but the more modern automobiles have a semiautomatic spark advance which operates with the speed of the engine.

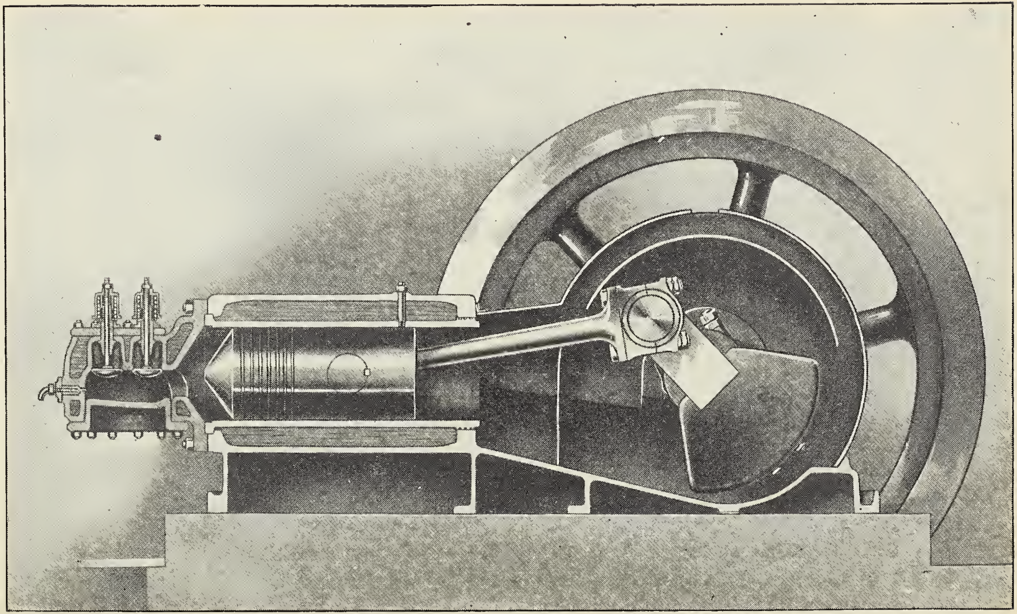
The Diesel and the semi-Diesel engine. The Diesel engine is a form of internal-combustion engine which depends for ignition of the fuel upon the heat developed by very high





An Early and a Modern Automobile

The upper picture shows a typical automobile of 1899. It had a 1-cylinder engine of about 9 horsepower and a wheel base of 72 inches. The drive was through a belt, and changes in speed were accomplished by slipping the belt. The lower picture shows a modern 6-passenger, 8-cylinder sedan. The engine develops 80 horsepower



A Semi-Diesel Oil Engine

compression of air within its cylinder. Into this highly compressed and very hot air the oil is injected as a spray under still higher pressure during the first part of the power stroke and burns nonexplosively, maintaining during this part of the stroke a pressure which is practically of constant value. The pressure then falls off during the remainder of the stroke.

In the semi-Diesel engine (shown on opposite page) the air is not compressed to as many hundred pounds to the square inch as in the full-Diesel type, and the oil burns much more rapidly, taking on to some extent the characteristics of an explosion. In the diagram two valves (the air valve and the exhaust valve) are shown immediately above the small compartment called the *vaporizer*. During the "suction" stroke to the right a cylinderful of air is driven in through the air valve by the outside pressure and then compressed into the vaporizer during the return stroke. Near the instant of maximum compression atomized oil is forced into the intensely hot air, where it ignites and causes the power stroke. Semi-Diesel engines are widely used because they are reliable, are simple in construction, and combine many of the best features of both the Diesel engine and the gas engine.

The full-Diesel engine is more complex, but is also reliable, economical, and adapted to a wide range of fuels from kerosene through heavy oils to tar spray. They are used on submarines and for a great variety of purposes on land, and are increasingly coming into use on large merchant ships and pleasure craft. They may, to some extent, replace steam locomotives, especially for short hauls and for use in arid regions. The *Gripsholm*, a 23,500-ton ship of the Swedish-American Line, is driven by two full-Diesel engines, each developing 17,000 horsepower at 125 revolutions per minute. Her speed is $17\frac{3}{4}$ knots. The *Kungsholm* is a sister ship.

Attempts have been made to adapt the Diesel engine for use in the automobile, to replace the conventional gasoline engine; and some preliminary trials appear encouraging, though no general use has yet developed.

Summary. **An internal-combustion engine has the heat for running it developed inside the cylinders, not outside as in the case of the steam engine. Its high efficiency is due to the very high temperature thus obtained in the cylinder.**

In the gas engine, combustion is brought about by means of a carefully timed electric spark, whereas in the Diesel engine the compression itself generates so much heat that combustion takes place without the need of a spark.

In the four-stroke type of gas engine the cycle consists of intake, compression, power, exhaust.

The principal mechanical parts of an automobile are the engine (including carburetor, ignition system, and cooling system), the clutch, the transmission, and the differential.

QUESTIONS AND PROBLEMS

A

1. Why is a gas engine called an internal-combustion engine?

2. (*a*) Why do gas engines have flywheels? (*b*) Why is a one-cylinder stationary gas engine of the four-stroke type (such as are commonly used for small-power purposes) especially in need of a flywheel?

3. Why will an automobile go up a hill in low gear (crankshaft revolving rapidly) when it would stall in high gear (crankshaft revolving slowly)?

4. Suppose the rear wheels of an automobile were keyed fast to a continuous axle (no differential), what would be the effect on the wear of rear tires in turning corners? Explain.

B

1. Several of the early automobiles were propelled by steam engines. What were (*a*) their advantages? (*b*) their disadvantages?

2. Give the number of power strokes per revolution in (*a*) a steam engine; (*b*) a two-cycle gas engine; (*c*) a four-cycle gas engine; (*d*) a Diesel engine.

3. Is a starter needed for (*a*) a steam engine? (*b*) a gas engine? (*c*) a Diesel engine?

4. From the graph on page 275 (*a*) find the driving speed for car No. 1 which would give the greatest gasoline economy. (*b*) At a speed of 60 mi/hr how far could one drive car No. 3 on 1 gal of gasoline?

CHAPTER XI

The Transference of Heat

Conduction

Conduction in solids. If one end of a short metal bar is held in the fire, the other end soon becomes too hot to hold; but if the metal rod is replaced by one of wood or glass, the end away from the flame is not appreciably heated.

This experiment shows that nonmetallic substances pass heat along less readily than do metallic substances. This method of transfer of heat energy is called conduction. But although all metals are good conductors as compared with nonmetals, they differ widely among themselves in their conducting powers.

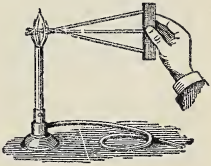


FIG. 215. Differences in the heat conductivities of metals

Twist together copper, iron, and German-silver wires 50 cm long and about 3 mm in diameter at one end, as in Fig. 215, and apply a Bunsen flame to the twisted ends. Slide a match slowly from the cool end of each wire toward the hot end, until the heat from the wire ignites it. The copper will be found to be the best conductor and the German silver (an alloy of nickel, zinc, and copper) the poorest.

In the following table some common substances are arranged in the order of their heat conductivities. The measurements have been made by a method not differing in principle from that just described. For convenience silver is taken as 100.

Silver	100	Tin	15	Mercury	1.5
Copper	74	Iron	12	Ice	.21
Aluminum	48	Lead	8.5	Glass	.15
Brass	27	German silver	6.3	Hard rubber	.04

Cooking utensils are often made of aluminum, and automobile radiators of copper, because of the readiness with which they conduct heat.

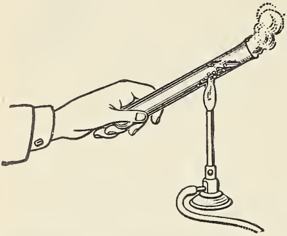


FIG. 216. Water a nonconductor

Conduction in liquids and gases. Hold a small piece of ice by means of a glass rod in the bottom of a test tube full of ice water. Heat the upper part of the tube with a Bunsen burner, as in Fig. 216. The upper part of the water may be boiled for some time without melting the ice. Water is evidently, then, a very poor conductor of heat. The same thing may be shown more strikingly as follows: Place the bulb of an air thermometer only a few millimeters beneath the surface of water contained in a large funnel arranged as in Fig. 217. If a spoonful of ether is poured on the water and set on fire, the index of the air thermometer will show scarcely any change, in spite of the fact that the air thermometer is a very sensitive indicator of changes in temperature.

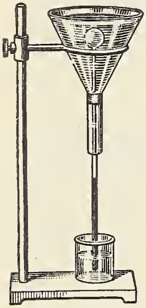


FIG. 217. Burning ether on the water does not affect the air thermometer

Careful measurements of the conductivity of water show that it is only about $\frac{1}{1200}$ that of silver. The conductivity of gases is even less, not amounting on the average to more than $\frac{1}{25}$ that of water. This is shown by the fact that one can hold his hand very close to a hot iron without being burned, as the air between is a poor conductor of heat. A vacuum is practically a nonconductor; that is, it is a heat-insulator.

Conductivity and sensation. On a cold day in winter a piece of metal feels much colder to the hand than a piece of wood, although a thermometer would show the temperature of the wood to be the same as that of the metal. On the other hand, if the same two bodies had been lying in the hot sun

in midsummer, the wood might be easily handled, but the metal would be uncomfortably hot. The explanation of these phenomena is found in the fact that the iron, being a much better conductor than the wood, removes heat from the hand much more rapidly in winter, and gives heat to the hand much more rapidly in summer, than does the wood. In general the better a conductor the hotter it will feel to a hand colder than itself, and the colder to a hand hotter than itself. Thus, in a cold room linoleum, a fairly good conductor, feels much colder to the touch than a carpet, a comparatively poor conductor. For the same reason linen clothing feels cooler to the touch in winter than woolen goods.

The role of air in nonconductors. Feathers, fur, felt, etc. make very warm coverings, because they are very poor conductors of heat and thus prevent the escape of heat from the body. Their poor conductivity is due in large measure to the fact that they are full of minute spaces containing "dead" air, and gases are the best nonconductors of heat. It is for this reason that freshly fallen snow is such an efficient protection to vegetation. Farmers always fear for their fruit trees and vines when there is a severe cold snap in winter, unless there is a coating of snow on the ground to prevent a deep freezing. The cellular structure of steam-pipe covering (Fig. 218) utilizes the nonconducting nature of air. Modern homes are now built with insulating materials (containing many tiny air spaces) placed between the walls and under the roofs. Not only is there a substantial saving in fuel costs during the winter, but the houses themselves are cooler in the summer. (See opposite page 288.)

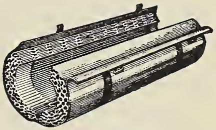


FIG. 218. Steam-pipe covering

[**The Davy safety lamp.** Place a piece of copper-wire gauze above an open gas jet and hold a lighted match above the gauze. The flame will be found to burn above the gauze, as in Fig. 219 (*a*), but it will not pass through to the lower side. If it is ignited below the gauze, the flame will burn as shown in Fig. 219 (*b*).

The explanation is found in the fact that the gauze conducts the heat away from the flame so rapidly that the gas on the other side is not raised to the temperature of ignition (called the kindling point). Before the invention of the electric lamp, safety lamps used by miners were completely incased in gauze, so that if the mine was full of inflammable gases they would not be ignited outside the gauze by the lamp. They were called Davy safety lamps.

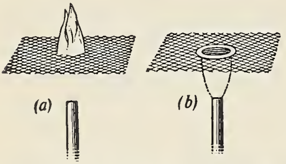


FIG. 219. A flame will not pass through wire gauze

Summary. **Conduction is the direct transference of heat through a solid or through a fluid from molecule to molecule.**

Metals are the best conductors, gases the poorest.

Of two hot bodies, the better conductor feels the hotter; of two cold bodies, the better conductor feels the colder.

The nonconducting power of loosely constructed bodies is due chiefly to the "dead" air they contain.

QUESTIONS AND PROBLEMS

A

1. If the ice in a refrigerator is wrapped up in blankets, what is the effect (*a*) on the ice? (*b*) on the refrigerator?

2. Why do firemen wear flannel shirts in summer to keep cool, and in winter to keep warm?

3. Why will a moistened finger or the tongue freeze instantly to a piece of iron on a cold winter's day, but not to a piece of wood?

4. Why is the outer pail of an ice-cream freezer made of thick wood and the inner can of thin metal?

5. Does clothing ever afford us heat in winter? How, then, does it keep us warm?

B

1. (*a*) In a steam-heating system why are the pipes that carry steam from the boiler to the radiators often covered with cellular asbestos? (*b*) Why is the cellular structure an advantage?

2. On a cold day chickens often ruffle their feathers, which makes them appear much larger than they really are. Why?

3. Why do storm windows on a house save fuel?

4. List four commercial materials sold for insulating houses.

5. If a piece of paper is wrapped tightly around a metal rod and held for an instant in a Bunsen flame, it will not be scorched. If held in a flame when wrapped around a wooden rod, it will be scorched at once. Explain.

6. If one touches the pan containing a loaf of bread in a hot oven, he receives a much more severe burn than if he touches the bread itself, although the two are at the same temperature. Explain.

Convection

Convection in liquids. Although the conducting power of liquids is very small, as was shown in the experiments on page 280, yet they are able, under certain circumstances, to transmit heat much more effectively than can solids. Thus, if the ice in the experiment of Fig. 216 had been placed at the top and the flame at the bottom, the ice would have been melted very quickly. This shows that heat is transferred very much more readily from the bottom of the tube toward the top than from the top toward the bottom. The way in which the heat is transferred is shown in the following experiment:

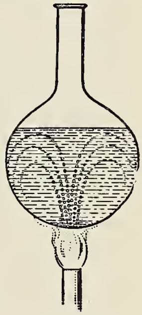


FIG. 220. Convection currents

Fill a round-bottomed flask (Fig. 220) half full of water and drop a few crystals of magenta into it. Then heat the bottom of the flask with a Bunsen burner. The magenta will reveal the fact that the heat sets up currents the direction of which is upward in the region immediately above the flame but downward at the sides of the vessel. It will not be long before the whole of the water is uniformly colored. This shows how thorough is the mixing accomplished by the heating.

The explanation of the phenomenon is as follows: The water nearest the flame became heated and expanded. It

was thus rendered less dense than the surrounding water, and was accordingly forced to the top by the pressure transmitted from the colder and therefore denser water at the sides, which then came in to take its place.

It is clear that, since the molecules of a solid cannot move freely from place to place, this method of heat transference may take place only in fluids, that is, liquids and gases. The essential difference between it and conduction is that the heat is not transferred from molecule to molecule throughout the whole mass, but rather is transferred by the bodily movement of comparatively large masses of the heated liquid from one point to another. This method of heat transference is known as *convection.*

Winds and ocean currents. Like liquids, air is a poor conductor of heat if kept at rest, but if free to move, it transfers heat readily by means of convection currents. Winds are convection currents in the atmosphere caused by unequal heating of the earth by the sun. Let us consider, for example, the land and sea breezes so familiar to all dwellers near the coasts of large bodies of water. During the daytime the land is heated more rapidly than the sea, because the specific heat of water is much greater than that of earth. Hence the hot air over the land expands and is forced up by the colder and denser air over the sea which moves in to take its place. This constitutes the sea breeze, which blows during the daytime, usually reaching its maximum strength in the late afternoon. At night the earth cools more rapidly than the sea, and hence the direction of the wind is reversed. The effect of these breezes is seldom felt more than twenty-five miles from shore.

Ocean currents are caused partly by the unequal heating of the sea and partly by the direction of the prevailing winds. In general both winds and currents are so modified by the shapes of the continents that it is only over broad expanses of the ocean that the direction of either can be predicted from simple considerations.

Radiation

A third method of heat transference. There are certain phenomena in connection with the transfer of heat for which conduction and convection are wholly unable to account. For example, if one sits in front of a hot grate fire, the heat which he feels cannot come from the fire by convection, because the currents of air are moving toward the fire rather than away from it. It cannot be due to conduction, because the conductivity of air is extremely small and the colder currents of air moving toward the fire would more than neutralize any transfer outward due to conduction. There must therefore be some way in which heat travels across the intervening space other than by conduction or convection.

This is still more evident when we consider the heat which comes to us from the sun. Conduction and convection take place only through the agency of matter; but we know that the space between the earth and the sun is not filled with ordinary matter, or else the earth would be retarded in its motion through space. *Radiation* is the name given to this third method by which heat travels from one place to another, and which is illustrated in the passing of heat from a grate fire to a body in front of it, or from the sun to the earth.

The nature of radiation. The nature of radiation will be discussed more fully in Chapter XXI. It will be sufficient here to call attention to the following differences between conduction, convection, and radiation.

First, while conduction and convection are comparatively slow processes, the transfer of heat by radiation takes place with the enormous speed with which light travels, namely 186,000 miles per second. That the two speeds are the same is evident from the fact that at the time of an eclipse of the sun the shutting off of heat from the earth is observed to take place at the same time as the shutting off of light.

Secondly, radiant heat travels in straight lines, whereas conducted or convected heat may follow the most circuitous routes. The proof of this statement is found in the familiar

fact that radiation may be cut off by means of a screen placed directly between a source and the body to be protected.

Thirdly, radiant heat may pass through a medium without heating it. This is shown by the fact that the upper regions of the atmosphere are very cold, even in the hottest days in summer, or that a greenhouse may be much warmer than the glass through which the sun's rays enter it.

Radiation and absorption. The sun, a fireplace, and an electric-light bulb all radiate energy. A body need not glow, however, to give off heat. A heated iron or a kettle of hot water will radiate heat. If the surface is polished, less heat will be radiated. White bodies usually radiate less heat than dark ones. Bodies that are good "radiators" are also good absorbers, and, conversely, poor "radiators" are poor absorbers. For this reason we wear white clothing in summer.

The newest cooking utensils are made with a dull-black surface underneath in order that they may absorb heat more readily from the flame. It is interesting to know that the usual aluminum or gold-bronze paint on steam and hot-water radiators will decrease the amount of heat thrown off (compared with the bare iron) by 7 per cent. On the other hand, a coat of linseed oil, zinc, and lithopone paint of cream color will *increase* the amount of heat given off by 4 per cent.

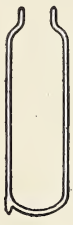


FIG. 221. The inner glass flask of a thermos bottle

The Dewar flask and the thermos bottle. To keep liquid air from evaporating too rapidly in his laboratory, Dewar invented a double-walled vessel. The space between the walls is a vacuum, and the inner surface of the outer vessel and the outer surface of the inner vessel are silvered. There are three ways in which heat may pass inward through the double wall — conduction, convection, and radiation. The vacuum almost entirely prevents the first two, and the silvering eliminates passage of heat by radiation. The glass part of the well-known thermos bottle (Fig. 221) is simply a cylindrical Dewar flask for keeping liquids either

hot or cold, since it is as difficult for heat to pass outward through the walls as to pass inward. The glass flask has a cork stopper, and a strong outside metal case for its protection. Hot liquids, as well as those that are cold, may be kept for several hours in a thermos bottle with only a few degrees change in temperature.

Huge vacuum bottles, holding as much as 2600 gallons of milk and mounted on automobile trucks, keep the milk cold while being transported to the bottling plants.

The Heating and Ventilating of Buildings

The principle of ventilation. The heating and ventilating of buildings are accomplished chiefly through the agency of convection.

To illustrate the principle of ventilation let a candle be lighted and placed in a vessel containing a layer of water (Fig. 222). When a lamp chimney is placed over the candle so that the bottom of the chimney is under the water, the flame will slowly die down and finally be extinguished. This is because the oxygen, which is essential to combustion, is gradually used up, and no fresh supply is possible with the arrangement described. If the chimney is raised even a very little above the water, the dying flame will at once brighten. Why? If a metal or cardboard partition is inserted in the chimney, as in Fig. 222, the flame will burn continuously even when the bottom of the chimney is under water. The reason will be clear if a piece of burning touch paper (blotting paper soaked in a solution of potassium nitrate and dried) is held over the chimney. The smoke will show the direction of the air currents. (If the chimney is a large one, in order that the first part of the experiment may succeed it may be necessary to use two candles; for too small a heated area permits the formation of downward currents at the sides. A spiral tube $\frac{1}{4}$ inch in diameter made of glazed paper and lighted at the center may be used instead of touch paper.)

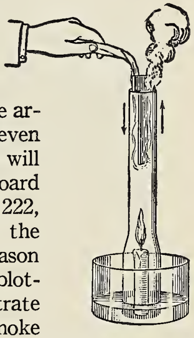


FIG. 222. Convection currents in air

Ventilation of houses. In order to secure satisfactory ventilation it is estimated that a room should be supplied with 2000 cubic feet of fresh air per hour for each occupant (a gas burner is equivalent in oxygen consumption to four persons). A current of air moving with a speed great enough to be just perceptible has a velocity of about 3 feet per second. Hence the area of opening required for each person when fresh air is entering at this speed is about 25 or 30 square inches. The manner of supplying this requisite amount of fresh air in dwelling houses depends upon the particular method of heating employed.

If a house is heated by stoves or fireplaces, no special provision for ventilation is needed. The foul air is forced up the chimney with the smoke by the entrance of the fresh air coming in through cracks about the doors and windows, and through the walls if highly porous.

[**Hot-air heating.** In houses heated by hot-air furnaces an air duct is sometimes supplied for the entrance of fresh cold air, in the manner shown in Fig. 223. (See "Cold air from out of doors.") This cold outdoor air is heated by passing in a circuitous way, as shown by the arrows, over the outer jacket of iron which covers the firebox. It is then delivered to the rooms. Here a part of it escapes through windows and doors, and the rest returns through the cold-air register to be mixed with a fresh supply from outdoors and reheated.

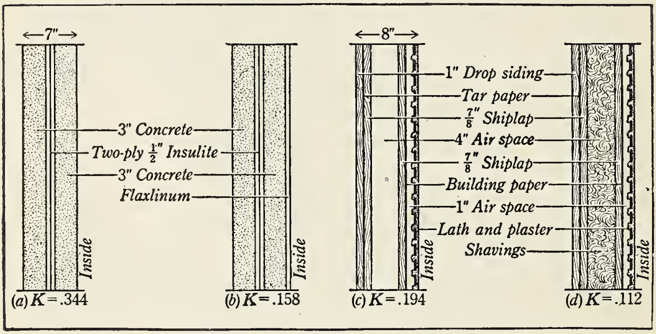
[When the fire is first started, in order to gain a strong draft the damper is opened so that all the smoke may pass directly up the chimney. After the fire is under way, the damper is closed so that the smoke and hot gases from the furnace must pass, as indicated by the arrow pointing into the dotted circle, over a roundabout path, in the course of which they give up the major part of their heat to the steel walls of the jacket, which in turn pass it on to the air which is on its way to the living-rooms.

[Such a furnace depends for its action on the convection currents set up in the air. It will change the air in each room on an average from one and a half to two times an hour. A

Ewing Galloway

Why didn't the Snow Melt on the Smiths' House? (See opposite page 289)

Rock-Wool Home Insulation in an Open Attic



Heat Insulation of Dwellings

It is estimated that an annual saving of at least $100,000,000 in fuel in the United States alone would be made if the walls of houses were properly constructed with respect to heat insulation. Such walls not only conserve heat in cold climates, but exclude it from houses in warm climates. The facts given on this page are the results of tests made at the University of Saskatchewan (with the aid of little windowless experimental houses) upon the thermal transmittance of the various walls shown. K is proportional to thermal transmittance, and in the units used the value of K for a solid concrete wall 7 inches thick was .782. It will be seen from the values of K that walls (*b*) and (*d*), although costing not appreciably more than (*a*) and (*c*) respectively, require about half the fuel to maintain the temperature constant. Taking the thermal transmittance of solid concrete as the base of comparison, we find the loss through (*a*) was 44 per cent of the loss through solid concrete; through (*b*), 20 per cent; through (*c*), 25 per cent; through (*d*), 14 per cent

more modern type uses a large propeller fan run by an electric motor and mounted in the top of the furnace. Increasing the changes of air to from four to ten times an hour, it has a number of advantages, such as quicker heating, more certain warmth in distant rooms, more uniform temperature (the ceilings of houses using the old type were much hotter than

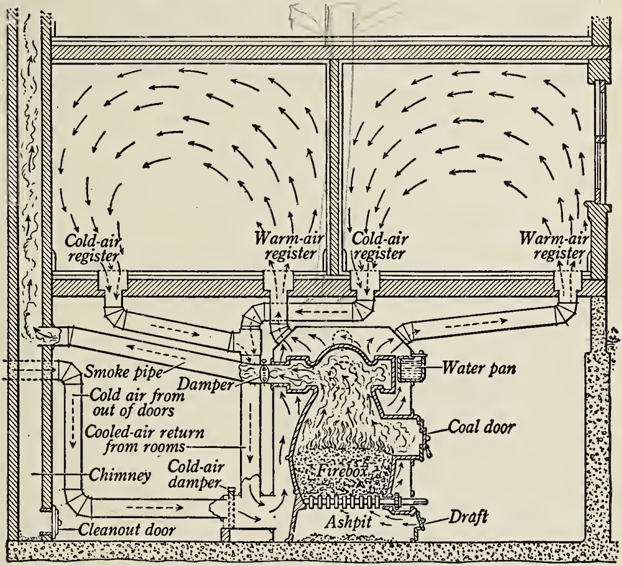


FIG. 223. Hot-air heating

the floor), and decreased heat losses in the basement. Such an arrangement affords a convenient way of humidifying the air throughout the house, as the warm air is forced past shallow pans of water kept filled by a connection with the water system of the house.

[In the summer, when the heat is turned off, the system functions to a certain extent as an air-conditioning unit. The basement air, which is always cooler than that of the

rest of the house, is taken in through filters and forced through the house, creating a current of air to bring about more comfortable and healthful living conditions. Another system forces the air from the intake through a water spray. If the incoming air is not too humid, the evaporation of the spray will notably cool the air passing through it. More elaborate and expensive types have a refrigerating unit similar to that of the electric refrigerator.

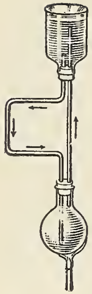


FIG. 224. Principle of hot-water heating

Hot-water and steam heating. To illustrate the principle of hot-water heating set up the arrangement shown in Fig. 224, the upper vessel being filled with colored water, and then apply a flame to the lower vessel. The colored water will show that the current moves in the direction of the arrows, carrying heat to the upper vessel.

This same principle is involved in the gas heating coil used in connection with the kitchen boiler (Fig. 225). Heat from the flame passes through the copper coil to the water, and convection begins as indicated by the arrows. When hot water is drawn from the top of the boiler, cold water enters near the bottom so as not to mingle with the hot water that is being used.

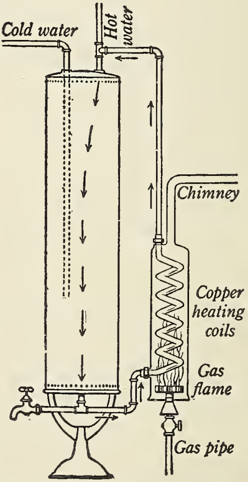


FIG. 225. A gas heating coil

The actual arrangement of boiler and radiators in one system of hot-water heating is shown in Fig. 226. The water heated in the boiler rises directly through the pipe *A* to a radiator *R*, and returns again to the bottom of the furnace through the pipes *B* and *D*. The circulation

is maintained because the column of water in *A* is hotter, and therefore possesses less density, than the water in the return pipe *B*.

[By eliminating the expansion tank and partly filling the boiler with water the system could be converted into the very commonly used steam-heating plant. This uses the high latent heat of condensation of water (539 calories) to give off a large amount of heat as the steam condenses. Its heat is less uniform, however, than the hot-water heat, and it is more difficult to manage in mild weather. Since steam radiators give off more heat than hot-water radiators, they need not be so large as the latter, and so take up less room.

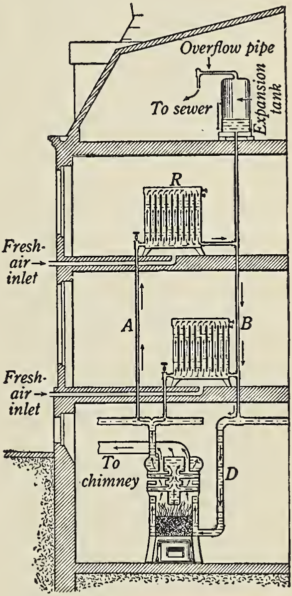


FIG. 226. Hot-water heater

[By placing a small motor-driven exhaust pump in the line, it is possible to combine the advantages of steam and hot water in *vapor-heating* systems. Reducing the pressure in the line causes the water to boil at a much lower temperature, and thus affords a low, steady, even heat. The installation is more expensive, of course, and every joint in the whole system must be airtight.

[Air valves (Fig. 227) are placed on steam radiators to allow air within the radiator to pass out ahead of the oncoming steam. Air escapes from the small hole *B*, and any water which enters the valve runs back into the radiator through the tube *T*. When the hot steam reaches the form of valve shown in Fig. 227, the vaporization of a volatile

liquid (ethyl chloride) in the closed capsule C (shown partly cut away) bulges the curved bottom downward, so that the capsule and pin A rise, closing the hole B.

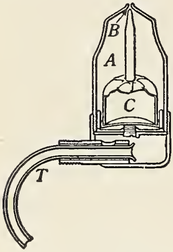


FIG. 227. A radiator air valve

[A more elaborate form, the *vacuum* valve, holds the opening shut for some time after the steam pressure has gone down. Since a partial vacuum exists in the system owing to the condensation of the steam (1600 cubic centimeters of steam form 1 gram of water), the water continues to boil at the reduced pressures. This steam at a much lower temperature condenses in the radiator, giving off a heat which approaches to some extent the more even heat of the hot-water system.

Summary. The transfer of heat energy from molecule to molecule is called conduction. Metals are better conductors than nonmetals, although they differ widely among themselves in their conductivity.

Convection is the transfer of heat energy through the rising of heated portions of fluids and the falling of colder and hence denser portions.

Radiation is the transfer through space, with the speed of light, of energy that appears as heat when absorbed by matter.

Heat radiations produce very little effect when they strike a polished silver surface, for they are almost wholly reflected.

Ventilation, hot-air heating, and hot-water heating are applications of convection. Air-conditioning may be most conveniently accomplished in the home in combination with the hot-air system of heating.

In steam heating every gram of steam that condenses in the radiators liberates 539 calories.

The use of insulating materials in the walls and roofs of houses enables us to live in greater comfort in both winter and summer and at the same time to reduce heating bills.

Radiator valves permit air, but not steam, to escape from the radiators.

QUESTIONS AND PROBLEMS

A

1. Give the relative advantages and disadvantages of the hot-air, steam, and hot-water systems of heating the home.

2. Discuss the convection currents occurring in connection with (*a*) the refrigerator; (*b*) the hot-air furnace; (*c*) the hot-water-heating system; (*d*) the steam-heating system; (*e*) land and sea breezes near coasts.

3. In what way do your hands receive heat from a hot radiator (*a*) when you touch it? (*b*) when you hold your hands at the side of it (not touching it)? (*c*) when you hold your hands a little above the radiator?

4. Explain the efficiency of a thermos bottle.

5. Why is it that a hollow wall filled with sawdust is a better nonconductor of heat than the same wall filled with air alone?

6. When a room is heated by a fireplace, which of the three methods of heat transference plays the most important role?

7. To make the proper use of convection currents, (*a*) where should the cooling unit be placed in an electric refrigerator? (*b*) where should a radiator be placed in a room? Draw simple diagrams showing the convection currents set up in each case.

8. With no fire in the fireplace, in what direction would the air tend to move in the chimney (*a*) in summer? (*b*) in winter? Why?

9. A bedroom has only one window. In summer, if the door must be kept closed, what is the best way of ventilating the room?

10. Housewives sometimes object to the large size of hot-water radiators because they interfere with the arrangement of furniture in a room. Why must they be larger than steam radiators of the same heating capacity?

B

1. From the standpoint of heat radiation and absorption, (*a*) what color should winter clothes have? (*b*) what finish should the sides of a teakettle have? (*c*) how should an automobile radiator be finished?

2. If we attempt to start a fire in the kitchen range when the chimney is cold, the range smokes. Explain.

3. In a system of hot-water heating why does the return pipe always connect at the bottom of the boiler, while the outgoing pipe connects with the top?

4. Discuss the equatorial trade winds as an application of convection currents. (See an encyclopedia.)

5. A well-known maker of vacuum bottles advertises that each quart bottle manufactured is put to the following test before being placed on the market: It is filled with boiling water, at 212° F., and allowed to stand 24 hr. If the temperature of the water goes below 150° F. (125° for pints), the bottle is destroyed. Test a bottle at school or at home to see if it meets these requirements. (*Caution:* To avoid possible breakage, fill with warm water before using the boiling water.)

6. During a period of 1 hr 4 kg of steam at 100° C. condensed in a radiator, and the temperature of the resulting water as it left the radiator was 92° C. How many calories of heat per second were made available during this time for heating the room?

7. Why are plants often covered with paper on a night when frost is expected?

8. If you open a door between a warm and a cold room, in what direction will a candle flame be blown which is placed at the top of the door? Explain.

9. Why should steam radiators be installed on the cold side of a room — for example, near outside walls or windows?

10. Name the essential parts for each of three different systems commonly employed for heating houses, and state the physical principles applied in each case which render it effective.

11. If 2 metric tons of coal are burned per month in your house, and if your furnace allows one third of the heat to go up the chimney, how many calories remain to be used per day? (Take 1 g as yielding 6000 cal. A metric ton = 1000 kg.)

UNIT FOUR

Electricity and Magnetism

The historical development of the field of electricity and magnetism furnishes an excellent illustration of how discoveries that at first look trivial lead little by little to the opening of new doors of knowledge — knowledge that in time revolutionizes the whole life of man.

Although in a sense the most fundamental facts of both magnetism and electricity were discovered by the Greeks hundreds of years before Christ, so far as we know they made no useful applications of these facts. No one knows who first thought of using a magnet as a compass; but it is quite certain that without the compass the Age of Geographical Discovery, as we know it, could not have existed.

Before the invention of the mariner's compass few dared to embark on voyages that took them to very great distances from familiar shores. Navigation on a large scale, now one of the most important of man's activities, probably owes its beginnings and its later enormous growth to the discovery that a freely suspended magnet always points nearly north and south. The social significance, then, of the study of the field of magnetism can scarcely be overestimated.

In an even more striking way the discovery of what we now call static electricity, described by Thales of Miletus in Asia Minor as early as 600 B.C., remained completely without social consequences for more than two thousand years. The first useful application was

Benjamin Franklin's invention of the lightning rod about 1750. Following him Volta the Italian, Oersted the Dane, Faraday the Englishman, and Ampère the Frenchman laid the foundation of the age of electricity in which we now live — an age in which the telegraph, the telephone, and the radio tell us what is happening all over the world. How stupendous an influence electricity has upon the lives of all of us is shown by the fact that not less than a twentieth of our population earns its living directly or indirectly through the electrical industry. This huge structure has grown out of the apparently trifling observation of Thales of Miletus. That section of physics which deals with electricity and magnetism tells the story of one of the most amazing and spectacular advances that the human race has ever made.

At first there was no known connection between magnetism and electricity, but in the nineteenth century the relation between them was discovered. Immediately thereafter the great Faraday showed how electric currents could be generated by moving electric conductors through a magnetic field.

The following chapters not merely tell the history of these developments, which have been so extraordinarily significant for the life of mankind, but also reveal how the laws have been discovered which make it possible to reduce electrical phenomena to an exact science and to design an electric dynamo or motor so that it will do any work required of it.

CHAPTER XII

Magnetism*

General Properties of Magnets

Magnets. Over two thousand years ago, in the time of the Greeks, someone among the people known as Magnetes in Thessaly noticed that certain pieces of a particular kind of ore would attract small bits of iron. The substance came to be known as the *Magnet stone*, from the place where it was discovered. Today it is called *magnetite*, and pieces of it which attract iron or steel are known as *natural magnets.* But beyond these chance discoveries the Greeks learned very little about magnetism because they knew little about the experimental method of investigating nature.

Hundreds of years later, in the twelfth century, someone more thoughtful than his fellows, probably in China, thought of hanging a magnet from its center so that it could turn in any direction. He noticed that it always took up the same position, one end pointing north, the other south. Sailors heard about this and began to use magnets to show them in what direction they were going, calling them lodestones (leading stones). But the method of thoughtful planned experiment was still unknown, and progress was very slow. Only since that method has become widely used, in the last hundred years, have the principles of magnetism and its many applications — the telephone, the telegraph, the electric motor, most instruments for measuring electric current, and many other applications — been worked out to add to the comfort and efficiency of mankind.

* This chapter should be either accompanied or preceded by laboratory experiments on magnetic fields and on the molecular nature of magnetism. See, for example, Experiments 31 and 32 of *Exercises in Laboratory Physics,* by Millikan, Gale, and Davis.

Artificial magnets are now made either by stroking bars of steel in one direction with a magnet or by passing electric currents about the bars in a manner to be described later. The form shown in Fig. 228 is called a *bar magnet*, and the one shown in Fig. 229 a *horseshoe magnet*. The latter form is the more common and is the more serviceable form for lifting pieces of iron or of steel.

FIG. 228. A bar magnet

If a magnet is dipped into iron filings, the filings will be seen to cling in tufts near the ends but scarcely at all near the middle (Fig. 230). These places near the ends of a magnet, at which its strength seems to be the greatest, are called the *poles* of the magnet. The end of a freely swinging magnet which points to the north is called the north-seeking pole or simply the *north pole* (N); the other end is called the south-seeking pole or the *south pole* (S). *The direction in which a compass needle points is called the magnetic meridian.*

FIG. 229. A horseshoe magnet


FIG. 230. Distribution of iron filings about a bar magnet

Laws of magnetic attraction and repulsion. In the experiment with the iron filings no particular difference was observed between the action of the two poles. That there is a difference, however, may be shown by experimenting with two magnets, either of which may be suspended (Fig. 231). If two N poles are brought near each other, they are found to repel each other. The S poles likewise are found to repel each other. But the N pole of one magnet is found to attract the S pole of another. The results of these experiments may be summarized in a general law: *Magnet poles of like kind repel each other, and poles of unlike kind attract each other.*

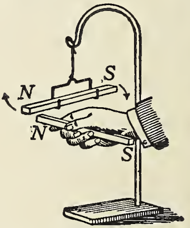


FIG. 231. Like poles repel; unlike poles attract

The force with which two unlike poles are drawn together or two like poles pushed apart is greater the greater the strength of the poles. The farther apart the poles are, the less this force becomes. This is stated more exactly by the following law: *The force which any two poles exert upon each other in air is equal to the product of the pole strengths divided by the square of the distance between them.*

A unit pole is defined as a pole which, when placed at a distance of 1 centimeter from an exactly equal and similar pole, in air, repels it with a force of 1 dyne.

Magnetic materials. Iron and steel are the only substances that are strongly attracted by magnets, though nickel and cobalt show a slight attraction. Bismuth, antimony, and a number of other substances are actually repelled instead ot attracted, but the effect is very small. It has recently been found possible to make strongly magnetic alloys out of certain non-magnetic materials. For example, a mixture of 65 per cent copper, 27 per cent manganese, and 8 per cent aluminum is strongly magnetic. These are called Heusler alloys. For practical purposes, however, iron and steel may be considered as the only magnetic materials.

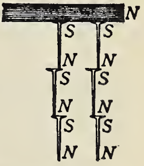


FIG. 232. Magnetism induced by contact

Magnetic induction. If a small unmagnetized nail is suspended from one end of a bar magnet, it is found that a second nail may be suspended from this first nail (which itself acts like a magnet), a third from the second, and so on, as shown in Fig. 232; but if the bar magnet is carefully pulled away from the first nail, the others will instantly fall away from one another, thus showing that the nails were strong magnets only so long as they were in contact with the bar magnet. Any piece of soft iron may be thus magnetized *temporarily* by holding it in contact with a permanent magnet. Indeed, it is not necessary that the two be actually touching, for if a nail is simply brought near to the permanent magnet it is found to become a magnet. This may be proved

by presenting some iron filings to one end of a nail held near a magnet in the manner shown in Fig. 233. They will cling to the nail as they would to a permanent magnet. Even inserting a plate of glass or of copper or of any other material except iron between S and N will not change appreciably the number of filings which cling to the end of S', a fact which shows that *nonmagnetic materials are transparent to magnetic forces.* As soon as the permanent magnet is taken away, however, most of the filings will fall. *Magnetism produced in a substance by the mere presence of near-by magnets, whether they touch the substance or not, is called induced magnetism.* If we test each end of the nail in Fig. 233 with a small compass needle, we find that the end farther from the permanent magnet is an S pole, *like the pole causing induction,* whereas that nearer the magnet is an N pole. This leads us to the general law of magnetic induction: *The remote induced pole is of the same kind as the inducing pole; the near pole is of unlike kind.*

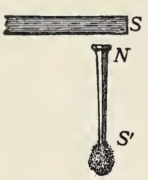


FIG. 233. Magnetism induced without contact

Magnetic induction explains the fact that a magnet attracts an unmagnetized piece of iron, for it first magnetizes it by induction, so that the near pole is unlike the inducing pole and the remote pole like the inducing pole. Since the force is greater for the smaller distance, the two unlike poles, being closer together, attract more strongly than the two like poles, farther apart, repel, and the piece of iron is drawn toward the magnet. Magnetic induction also explains the formation of the tufts of iron filings shown in Fig. 230, each little filing becoming a temporary magnet such that the end pointing toward the inducing pole is unlike this pole, and the end pointing away from it is like this pole. The bushlike appearance is due to the repelling action which the outside free poles exert upon each other.

Retentivity and permeability. A piece of soft iron brought near a permanent magnet will very easily become a strong temporary magnet; but when it is taken away from the

permanent magnet, it loses practically all its magnetism. On the other hand, a piece of steel will not be so strongly magnetized as the soft iron, but it will keep much more of its magnetism after it is taken away from the permanent magnet. This quality of resisting either magnetization or demagnetization is called *retentivity*. Thus steel has a much greater retentivity than wrought iron, and, in general, the harder the steel the greater its retentivity.

A substance which becomes strongly magnetic when near a permanent magnet, whether it has a high retentivity or not, is said to possess *permeability* in large degree. Thus, though soft iron does not hold, or *retain*, its magnetism and so has low retentivity, it is strongly magnetized as long as the permanent magnet is near and so has high permeability. A new compound of iron and nickel called "Permalloy" has been discovered which in weak fields has a permeability thirty times that of soft iron.

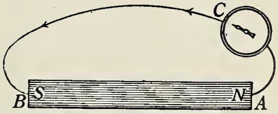


FIG. 234. A line of force set up by the magnet *AB*

Magnetic lines of force. If we could separate the *N* and *S* poles of a small magnet so as to get an *N* pole all by itself, and if we were to place this *N* pole near the *N* pole of a bar magnet, it would move over to the *S* pole along some curved path similar to that shown in Fig. 234. The reason it would move in a curved path is as follows: It would be repelled by the *N* pole and attracted by the *S* pole at the same time. But when it was nearer the *N* pole, the *N* pole would repel it more strongly than the *S* pole would attract it. It would hence move out from the magnet as it moved from *N* to *S*. As it moved farther to the left and thus nearer the *S* pole, the attraction of *S* would become greater than the repulsion of *N*. It would hence come in toward the magnet again.

To prove that this is what would happen, push a strongly magnetized sewing needle vertically into a small cork. Float the cork in a shallow dish of water so that one end of the needle sticks down into

the water and the other sticks up into the air. Place a bar magnet or horseshoe magnet just below the dish (Fig. 235). The cork and the needle will then move as would an independent pole, since the remote pole of the needle, in the air, is so much farther from the magnet than the near pole, in the water, that its influence on the motion is very small. The cork will actually be found to move in a curved path from N to S.

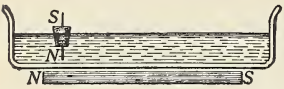


FIG. 235. Showing direction of motion of an isolated pole near a magnet

Any path which an N pole by itself would take in going from N to S is called a *line of force*. The simplest way of finding the direction of this path at any point near a magnet is to hold a short compass needle at the point considered. The needle sets itself along the line in which its poles would move if independent of each other; that is, along the line of force which passes through the given point. (See C, Fig. 234.)

Fields of force. The space around a magnet in which we can see the influence of the magnet on a compass needle, that is, the space in which its magnetic forces can be detected, is called its *field of force*. The easiest way of gaining an idea of the way in which the lines of force are arranged in the

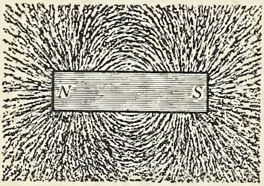


FIG. 236. Arrangement of iron filings about a bar magnet

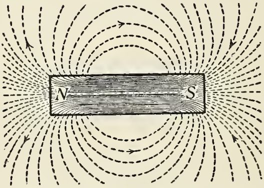


FIG. 237. Ideal diagram of field of a bar magnet

magnetic field about any magnet is to sift iron filings upon a piece of paper placed just over the magnet. Each little filing becomes a temporary magnet by induction, and therefore, like the compass needle, sets itself in the direction of the line of force at the point where it is. Fig. 236 shows how the

filings arrange themselves about a bar magnet. Fig. 237 is the corresponding ideal diagram showing the lines of force coming out from the *N* pole and passing about in curved paths to the *S* pole. It is customary to imagine these lines as returning through the magnet from *S* to *N* in the manner shown, so that each line is thought of as a closed curve. This convention was introduced by Faraday, and has been found very helpful in relating the facts of magnetism to one another. Figs. 238 and 239 show the arrangement of iron filings (1) between unlike poles and (2) between like poles. It will be noticed that lines of force never cross one another.

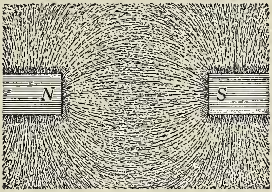


Fig. 238. Iron filings between unlike poles

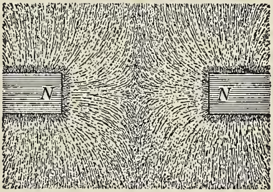


Fig. 239. Iron filings between like poles

If a magnetic pole is placed in a magnetic field, it will be acted upon by a force tending to move it along a line of force. *A magnetic field of unit strength is defined as a field in which a unit magnet pole is acted upon by 1 dyne of force.* Such a unit field of force is by custom usually shown by taking a surface such as *ABCD* (Fig. 240) at right angles to the lines of force and drawing one line through each square centimeter of the surface. Thus the strength of a field of force at any point, or its *density*, is shown by the number of lines of force passing through a surface 1 centimeter square at right angles to the lines. If a unit *N* pole between *N* and *S* (Fig. 240) were pushed by the magnetic field toward *S* with a force of 1000 dynes, the strength of the field would be 1000 units, and it would be represented by 1000 lines per square centimeter. In short, *the density of the lines of force in a region shows the strength of the magnetic field in that region.*

We learned on page 300 that nonmagnetic materials are transparent to magnetic forces. We may now state this another way by saying that lines of force pass through nonmagnetic materials almost wholly undeflected. On the other hand, if we enclose a compass in an iron or steel box and place the box in a magnetic field, the magnetic forces which control the direction of the compass needle will be found to be very greatly weakened. This is because lines of force find an easier path through magnetic materials than through air, and are turned aside so as to remain in the iron or steel as long as possible. Thus the lines of force of the magnetic field in Fig. 241 are carried around from one side of the ring to the other mostly in the iron, as shown in (*b*), instead of passing through air, as in (*a*). In the same way the lines of the earth's magnetic field tend to be carried around the iron or steel hulls of ships and submarines.

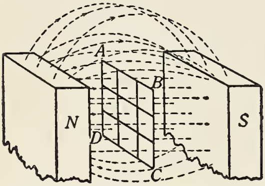


FIG. 240. The strength of a magnetic field is represented by the number of lines of force per square centimeter

Nature of magnetism. If a small test tube full of iron filings is stroked from end to end with a magnet, it will be found to have become itself a magnet; but it will lose its magnetism as soon as the filings are shaken up. If a magnetized knitting needle is jarred or hammered or twisted, the number of iron filings it will pick up will be much less than before, showing that the pole strength of the needle has been greatly reduced. Again, if such a needle is heated red-hot, it will lose its magnetism completely.

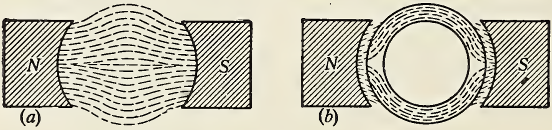


FIG. 241. Lines of force deflected by an iron ring

These facts point to the conclusion that magnetism has something to do with the arrangement of the atoms, molecules, or groups of molecules, since causes which violently disturb the particles within a magnet weaken its magnetism. Again, if a magnetized needle is broken, each part will be found to be a complete magnet; that is, two new poles will appear at the point of breaking: a new N pole on the part which has the original S pole, and a new S pole on the part which has the original N pole. The subdivision may be continued indefinitely, but always with the same result, as indicated in Fig. 242. This suggests that some very small particles within a magnetized bar may themselves be little magnets arranged in rows with their opposite poles in contact.

FIG. 242. Effect of breaking a magnet

If an unmagnetized piece of hard steel is pounded vigorously while it lies between the poles of a magnet, or if it is heated to redness and then allowed to cool in this position, it will be found to have become magnetized. This suggests that some very small particles within the steel are magnets even when the bar as a whole is not magnetized, and that magnetization may consist in causing them to arrange themselves in rows, end to end, just as the magnetization of the tube of iron filings mentioned above was due to a special arrangement of the filings.

FIG. 243. Arrangement of particles in an unmagnetized iron bar

Theory of magnetism. In an unmagnetized bar of iron or steel it is probable, then, that some very small particles within the bar are tiny magnets which are arranged either without order or in little closed groups or chains, as in Fig. 243, so that, on the whole, opposite poles neutralize each other throughout the bar. But when the bar is brought near

a magnet, these particles are swung around by the outside magnetic force into an arrangement somewhat like the one shown in Fig. 244, where the opposite poles completely neutralize each other only in the middle of the bar. According to this view, heating and jarring weaken the magnet because they tend to shake the particles out of line. On the other hand, heating and jarring help magnetization when the bar is between the poles of a magnet because they assist the magnetizing force in breaking up closed magnetic groups and chains and getting the individual tiny magnets into line. Soft iron has higher permeability than hard steel because the particles of the iron are much less rigidly held in position, and hence are much easier to swing into alignment than those of the steel. Steel has a very much greater retentivity than soft iron because its particles are not so easily moved out of position when once they have been aligned.

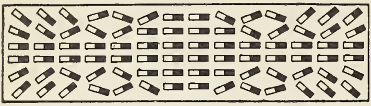


FIG. 244. Arrangement of particles in a magnetized iron bar

Saturation. An experimental fact strongly supporting this theory is that a piece of iron or steel cannot be magnetized beyond a certain limit, no matter how strong the magnetizing force is. This limit probably corresponds to the condition in which all the tiny magnets are brought into line, as in Fig. 245. The magnet is then said to be *saturated,* since it is as strong as it is possible to make it.

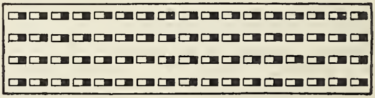
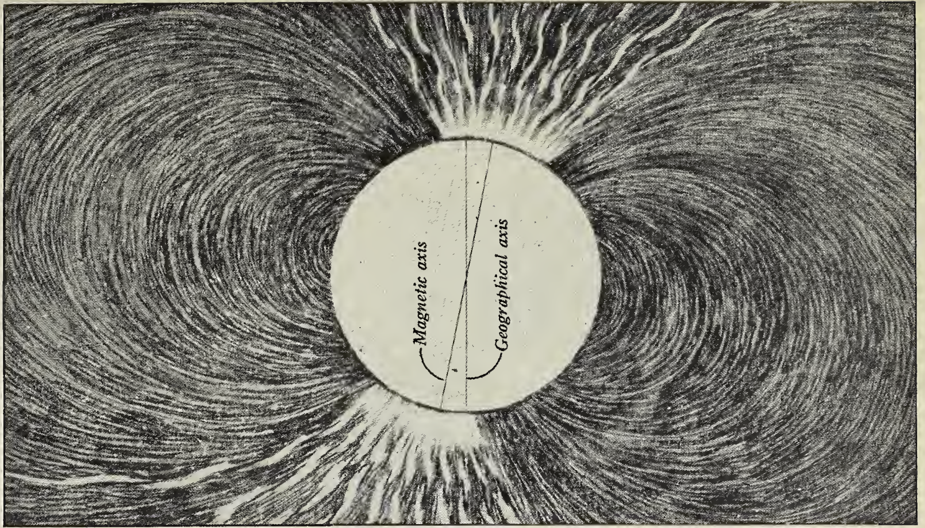


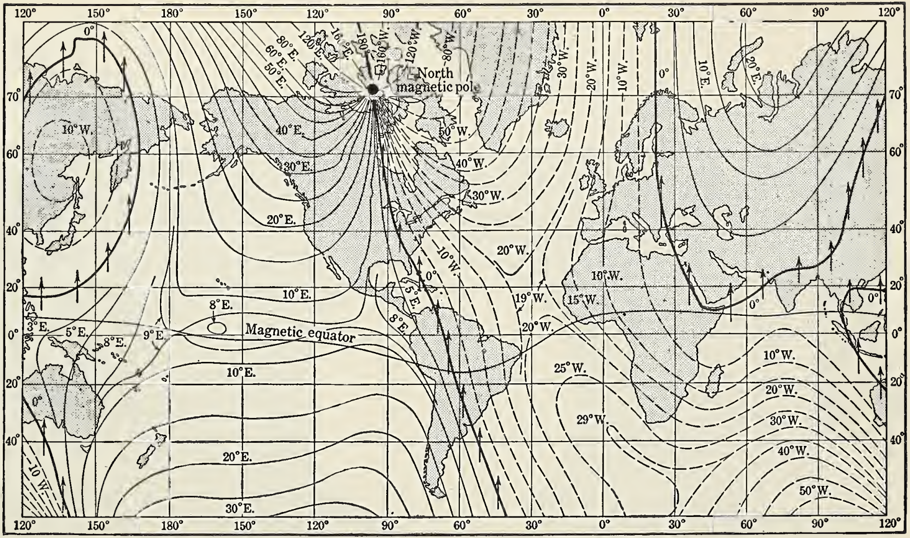
FIG. 245. Arrangement of particles in a saturated magnet

Just what kind of particles constitute the tiny magnets within the body of the bar, it is not possible to say with definiteness. Thus the so-called Heusler alloys show strong magnetic properties in spite of the fact that the constituent elements going into these alloys are all unmagnetic.



The Earth's Magnetic Field

The figure shows the shape of the field and the displacement of the magnetic from the geographical poles. The earth's atmosphere extends but a few hundred miles, at most, from the surface, but the magnetic field should be appreciable to a distance of 12,000 miles. At 4000 miles its intensity is one eighth as much as at the surface. (From an original drawing by W. J. Peters of the staff of terrestrial magnetism, Carnegie Institution of Washington)



The Earth's Magnetic Equator and Isogonic Lines

The first line starting just above 0° is the magnetic equator — line of no magnetic *dip*. The lighter isogonic lines, of enormous value to sailors, show everywhere the angle between the compass needle and true north. The heavier isogonic lines show where the needle points due north, — where *declination* is zero

Terrestrial Magnetism

The earth's magnetism. In the sixteenth century it was thought that a compass needle pointed nearly north and south because of some mysterious influence of the stars. William Gilbert, physician to Queen Elizabeth and the first Englishman to understand the value of the experimental method, proved that this was unfounded superstition. He showed by a famous experiment that the earth is in reality itself a great magnet. He made a small sphere of magnetite and found that a compass needle laid in various places on the sphere acted in the same way as a compass needle held at corresponding places on the earth. He wrote about this discovery and many others in a book, *De Magnete etc.*, published in London in 1600, which showed how facts are found not by guesswork but by experiment.

The fact that the N pole of a compass needle points north shows that the earth has an S pole near the geographic north pole and an N pole near the geographic south pole; for the magnetic pole of the earth near the geographic north pole must of course be unlike the pole of a freely suspended magnet which points toward it, and the pole of the freely suspended magnet which points toward the north is the one which, by convention, it has been decided to call the N pole. The magnetic pole of the earth which is near the north geographic pole was found in 1831 by Sir James Ross in Boothia, Canada, latitude 70° 30′ N., longitude 95° W. It was located again in 1905 by Captain Amundsen (the discoverer of the geographic south pole in 1912) at a point a little farther west. Its location is about 70° 5′ N. and 96° 46′ W. Careful observations seem to show that it shifts its position slowly. The other magnetic pole is in the Antarctic at latitude 72° 25′ S. and longitude 155° 16′ E. It was located by a party from the Shackleton expedition in 1909.

Declination. The earliest users of the compass were aware that it did not point exactly north; but it was Columbus who, on his first voyage to America, made the discovery,

much to the alarm of his sailors, that the direction of the compass needle changes as one moves about over the earth's surface. The chief reason for this variation is that the magnetic poles do not coincide with the geographic poles; but there are also other causes, such as the existence of large deposits of iron ore, which deflect the needle from the magnetic north. *The number of degrees which the north pole of a compass needle at any given place on the earth points away from the true geographic north is called its declination* at that place. Each of the lines in the map opposite page 307 is so drawn that at each point on it the declination is the same. Lines drawn over the earth through points of equal declination are called *isogonic lines.* The heavy lines pass through all the points where the needle points exactly to the north. These lines correspond, therefore, to places where the declination is zero. Lines of zero declination are called *agonic lines.*

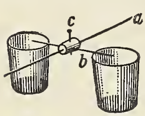


FIG. 246. Arrangement for showing dip

The dipping needle. Thrust an unmagnetized knitting needle *a* (Fig. 246) through a cork, and insert a second needle *b* as shown. Adjust a pin *c* until the system is in neutral equilibrium about *b* as an axis, when *a* is pointing east and west. Then carefully magnetize *a* by stroking one end of it, from the middle out, with the *N* pole of a strong magnet, and the other end, from the middle out, with the *S* pole of the same magnet. If the needle is allowed to swing in a north-and-south vertical plane it will dip at an angle of from 60° to 70° with the horizontal, *N* pole downward.

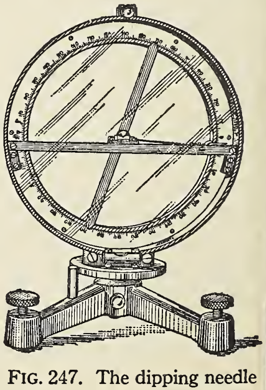


FIG. 247. The dipping needle

The experiment shows that in this latitude the earth's magnetic lines make a large angle with the horizontal. *This angle between the earth's surface and the direction of the magnetic lines is called the dip,*

or inclination, of the needle. At Washington it is 71° 5′, and at Chicago 72° 50′. At the magnetic pole it is of course 90°, and at the so-called *magnetic equator*, which is an irregular curved line near the geographic equator, the dip is 0° (see map opposite page 307). The dipping needle is shown in Fig. 247.

The earth's inductive action. That the earth acts like a great magnet may be very strikingly shown in the following way:

Hold a steel rod (for example, a tripod rod) parallel to the earth's magnetic lines (the north end slanting down at an angle of about 70° or 75°) and strike it a few sharp blows with a hammer. The rod will be found to have become a magnet with its upper end an *S* pole, like the north pole of the earth, and its lower end an *N* pole. If the rod is reversed and tapped again with the hammer, its magnetism will be reversed. If it is held in an east-and-west position and tapped, it will become demagnetized, as will be shown by the fact that either end of it will attract either end of a compass needle. In some respects a soft-iron rod is more satisfactory for this experiment than a steel rod, on account of the smaller retentivity. An alloy of cobalt, nickel, and iron has recently been made, having so high a permeability that when two strips of it are merely placed end to end parallel to the earth's field, one of them will support the other.

Summary. **Like poles repel; unlike poles attract.**

A unit pole is one which at a distance of 1 centimeter from an equal and similar pole repels it with a force of 1 dyne.

A magnetic line of force is the path along which an independent *N* pole tends to move.

A magnetic field of unit strength is one in which a unit pole experiences 1 dyne of force.

The number of lines of force in a region is a measure of the strength of the magnetic field in the region.

The declination at a given locality is the number of degrees by which the *N* pole points away from the true north.

The dip, or inclination, in a given locality is the angle between a horizontal plane and the direction of the dipping needle.

The magnetic equator is an irregular line drawn over the earth through points where the dip is zero.

QUESTIONS AND PROBLEMS

A

1. Devise an experiment which will show that a piece of iron attracts a magnet just as truly as the magnet attracts the iron.

2. In testing a needle with a magnet to see if the needle is magnetized why must you get *repulsion* before you can be sure it is magnetized?

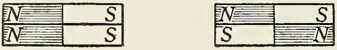
3. Given two bar magnets, the poles of which are not marked, how would you (*a*) locate the north-seeking pole of each? (*b*) determine which is the more strongly magnetized?

4. Make a diagram to show the general shape of the lines of force (*a*) between unlike poles of two bar magnets; (*b*) between like poles.

5. When a piece of soft iron is made a temporary magnet by bringing it near the *N* pole of a bar magnet, will the end of the iron nearest the magnet be an *N* pole or an *S* pole? Explain.

6. Explain, on the basis of induced magnetization, the process by which a magnet attracts a piece of soft iron.

7. Two bar magnets of equal strength are combined as in Fig. 248 (*a*) and then as in Fig. 248 (*b*). Diagram their magnetic lines of force as you imagine them to be in the two cases. Test by using iron filings and cardboard; also by lifting a bunch of small nails.



(*a*) (*b*)

FIG. 248

8. Examine the map opposite page 307 and tell where a compass would point (*a*) north; (*b*) south; (*c*) east; (*d*) west.

9. Examine the map opposite page 307 to locate the line of no dip (the magnetic equator). Does it ever coincide with the geographic equator? If so, where?

B

1. A strip of iron is always laid across the poles of a horseshoe magnet when the magnet is not in use. (*a*) Why? (*b*) Why must this strip be removed before the magnet will pick up magnetic materials?

2. A magnetic pole of 80 units strength is 20 cm distant from a similar pole of 30 units strength. Find the force between them.

3. If a bar magnet is floated on a piece of cork, will it tend to float toward the north? Why? Try it.

4. Why should the needle used in the experiment on page 308 be placed east and west when adjusting for neutral equilibrium before it is magnetized?

5. The dipping needle is suspended from one arm of a steel-free balance and carefully weighed. It is then magnetized. Will its apparent weight increase? Try it.

6. (*a*) How would an ordinary compass needle act if placed over one of the earth's magnetic poles? (*b*) How would a dipping needle act at this point?

7. From the map find the declination in the vicinity (*a*) of Maine; (*b*) of California.

8. (*a*) Why, in general, are the tops of radiators throughout the United States *S* magnetic poles, as shown by their repelling the *S* pole of a compass? (*b*) What, in general, is the polarity of the tops of radiators in South America?

9. Why is the gyrocompass now used on many submarines and battleships?

10. Can you pick up a piece of a tin can with a magnet? Try it. Explain.

11. Why do men working about large dynamos and motors carry their watches in iron cases?

CHAPTER XIII

Static Electricity

General Facts of Electrification

Electrification by friction. Rub a rod of hard rubber with flannel and then bring it near a dry bit of paper. The paper will jump toward the rod. The experiment seems trivial enough; yet from it has sprung our modern electrical world. It began with that same Thales of Miletus who first noticed magnetic attraction. He commented on the fact that a piece of amber, when rubbed with the fingers, draws to itself threads and other light objects. People were content to let this fact stand for two thousand years without looking into it further. But in 1600 A.D. William Gilbert, sometimes called the father of the modern science of electricity and magnetism, applied the experimental method to the problem and found that many other substances when rubbed together would act in the same way as amber and the fingers, such, for example, as glass and silk, and sealing wax and flannel.

The effect produced by rubbing these various substances is now called *electrification,* after the Greek word *elektron,* meaning "amber." *Thus a body which, like rubbed amber, has acquired the property of attracting light bodies is said to have been electrified, or to have been given a charge of electricity.* In this statement nothing is said about the nature of electricity. We simply define an electrically charged body as one that has been put into the condition in which it acts toward light bodies like the rubbed amber or the rubbed sealing wax. We do not know with certainty what the ultimate nature of electricity is, but we are fairly sure of the laws that govern its action. The following sections deal with these laws.

Positive and negative electricity. Rub a glass rod with silk and hang it from its center, as in Fig. 249. Rub another glass rod with silk and bring it near the first. The first is found to be repelled. Now rub an ebonite (hard rubber) or sealing-wax rod with cat's fur or flannel and bring it near the hanging rod. The two rods will be found to attract each other.

Evidently, then, the electrifications imparted to glass by rubbing it with silk and to sealing wax by rubbing it with flannel are opposite in the sense that an electrified body which is attracted by one is repelled by the other. We say, therefore, that there are two kinds of electrification. Benjamin Franklin arbitrarily introduced the terms *positive* and *negative*, or + and −, to designate these two kinds of electrification. Thus a *positively electrified body* is one which acts with respect to other electrified bodies like a *glass rod that has been rubbed with silk*, and a *negatively electrified body* is one which acts like a piece of *sealing wax that has been rubbed with flannel.* These facts and definitions may be stated in the following general law: *Electrical charges of like kind repel each other, and charges of unlike kind attract each other.* The forces of attraction or repulsion are found, like those of gravitation and magnetism, *to decrease as the square of the distance increases.*

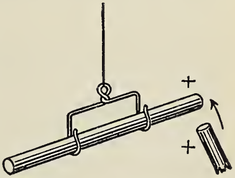


FIG. 249. Like charges repel

Measurement of electrical quantities. As we have seen, to conduct accurate experiments we must find out not only how and why but how much. We define so-called quantities of electricity in terms of attraction and repulsion. Thus a small charged body is said to contain 1 unit of electricity when it will repel with a force of 1 dyne an exactly equal and similar charge placed 1 centimeter away. The number of units of electricity on any charged body is then measured by the force that it exerts upon a unit charge placed at a given distance from it; for example, a charge that at a distance of 10 centimeters repels a unit charge with a force of 1 dyne contains

100 units of electricity, for this means that at a distance of 1 centimeter it would repel the unit charge with a force of 100 dynes.

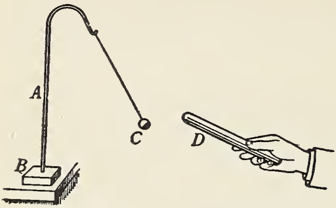


FIG. 250. Pith-ball electroscope

The electroscope. An electroscope is any instrument which may be used for detecting the presence on any body of an electrical charge. One of its simplest forms is a pith ball hung on the end of a silk thread, as in Fig. 250. Once such a ball has been given a charge by touching it to an electrified body, it will be attracted or repelled by other electrified bodies, depending upon the sign of the charge they carry. The most convenient form of electroscope, however, is that shown in Fig. 251, *a* and *b* representing strips of gold leaf.

Conductors and nonconductors. Connect an electroscope *E* (Fig. 251), consisting of a pair of gold leaves *a* and *b* hung from an insulated metal rod *r* and protected from air currents by a case *J*, with the metal ball *B* by means of a wire. Now electrify an ebonite rod and rub it over *B*. The gold leaves will immediately spread apart, showing that a portion of the electrical charge placed upon *B* has been carried by the wire to the gold leaves, where it makes them spread apart in accordance with the law that bodies charged with the same kind of electricity repel each other.

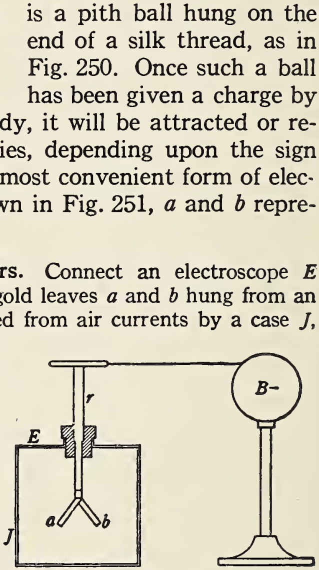


FIG. 251. Illustrating conduction

Repeat the experiment when *E* and *B* are connected with a thread of silk or a long rod of dry wood, such as a meter stick, instead of the metal wire. No divergence of the leaves will be observed. If a moistened thread connects *E* and *B*, the leaves will be seen to diverge slowly when the ball *B* is charged, showing that a charge is carried slowly by the moist thread.

These experiments make it clear that while electrical charges pass with perfect readiness from one point to another in a wire, they are quite unable to pass along dry silk or wood, and pass with difficulty along moist silk. We are therefore accustomed to divide substances into two classes, *conductors* and *nonconductors* (or *insulators*), according to their ability to transmit electrical charges from point to point. Thus metals and solutions of salts and acids in water are all conductors of electricity, and glass, porcelain, rubber, mica, shellac, wood, silk, vaseline, turpentine, paraffin, and oils are insulators. No hard-and-fast line, however, can be drawn between conductors and nonconductors, since all so-called insulators conduct to some slight extent, and the so-called conductors differ greatly in the ease with which they transmit charges.

Distinction between magnetism and electricity. The fact of conduction brings out sharply one of the most essential distinctions between electricity and magnetism. Magnetic poles exist only in iron and steel; electrical charges may be given any body whatever, provided it is insulated. These charges pass over conductors and can be transferred by contact from one body to any other, whereas magnetic poles remain fixed in position and are unaffected by contact with other bodies unless these bodies are themselves magnets.

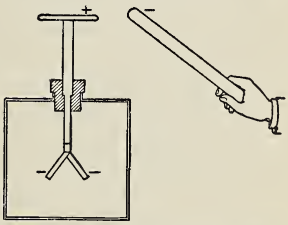


FIG. 252. Illustrating induction

Electrostatic induction. Electrify the ebonite rod by friction and slowly bring it toward the knob of the gold-leaf electroscope (Fig. 252). The leaves will be seen to diverge, even though the rod does not approach to within a foot of the electroscope.

This makes it clear that the mere *influence* which an electrical charge exerts upon a conductor placed in its neighborhood is able to produce electrification in that conductor.

This method of producing electrification is called *electrostatic induction.*

As soon as the charged rod is removed, the leaves will be seen to collapse completely. This shows that this form of electrification is only a temporary phenomenon which is due simply to the presence of the charged body in the neighborhood.

Nature of electrification produced by induction. Let a metal ball *A* (Fig. 253) be strongly charged by rubbing it with a charged rod, and let it then be brought near an insulated* metal body *B* provided with pith balls or strips of paper *a*, *b*, *c*, as shown. The divergence of *a* and *c* will show that the ends of *B* have received electrical charges because of the presence of *A*, and the failure of *b* to diverge will show that the middle of *B* is uncharged. Furthermore, the rod that charged *A* will be found to repel *c* but to attract *a*.

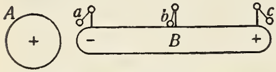


FIG. 253. Nature of induced charges

We conclude, therefore, that *when a conductor is brought near a charged body, the end away from the inducing charge is electrified with the same kind of electricity as that on the inducing body, while the end toward the inducing body receives electricity of the opposite kind.*

The electron theory of electricity. The atoms of all substances are now known to contain as constituents both positive and negative electricity, the latter existing in the form of minute particles (electrons) each of which has a mass $\frac{1}{1836}$ of that of the hydrogen atom. In each atom these electrons are grouped in some way about the positive electricity as a nucleus. The sum of the negative charges of these electrons is equal to the positive charge of the nucleus, so that in its normal condition the whole atom is neutral, or uncharged. But in conductors electrons are continually getting loose from the atoms and re-entering other atoms, so that

* Sulfur is practically a perfect insulator in all weathers, wet or dry. Metal conductors of almost any shape resting upon pieces of sulfur will serve the purposes of this experiment in summer or winter.

at any given instant there are in every conductor a number of free negative electrons and a corresponding number of atoms which have lost electrons and which are therefore positively charged. Such a conductor would, as a whole, show no charge of either positive or negative electricity. But as soon as a body charged, for example, positively (Fig. 253) is brought near such a conductor, the free negative electrons are attracted to the near end, leaving behind them the positively charged but immovable atoms. On the other hand, if a negatively charged body is brought near the conductor, the negative electrons stream away and the near end is left with the immovable positive atoms. As soon as the inducing charge is removed, the conductor becomes neutral again, because the little negative particles return to their former positions under the influence of the attraction of the positive atoms. This is the present-day picture of the way in which electrification is produced by induction.

The charge of one electron is called the elementary electrical charge. Its value was first accurately measured about 1912. There are 2,095,000,000 of them in one of the units defined on page 313. *Every electrical charge consists of an exact number of these ultimate electrical atoms.*

Charging by induction. Suspend two metal balls or two eggshells, A and B, which have been gilded or covered with tin foil, by silk threads and touch them together, as in Fig. 254. Bring a positively charged body C near them. As described above, A and B will at once exhibit evidences of electrification; that is, A will repel a positively charged pith ball, and B will attract it. If C is removed while A and B are still in contact, the separated charges reunite and A and B cease to exhibit electrification; but if A and B are separated from each other while C is in place, A will be found to remain positively charged and B negatively charged. This may be proved either by the attractions and repulsions which they show for charged rods brought near them or

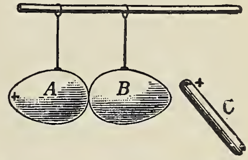


FIG. 254. Obtaining a plus and a minus charge by induction

by the effects produced upon a charged electroscope brought into their vicinity, the leaves falling together when it is brought near one and spreading apart when it is brought near the other.

We see, therefore, that *if we cut in two, or separate into two parts, a conductor while it is under the influence of an electrical charge, we obtain two permanently charged bodies, the remoter part having a charge of the same sign as that of the inducing charge, and the near part having a charge of unlike sign.* The negative electrons, attracted by the positive charge on *C*, moved out of *A* into *B*, which act made *A* positive and *B* negative.

Let the insulated conductor *B* (Fig. 255) be touched at *a* by the finger while a positively charged rod *C* is near it. Then let the finger be removed, and after it the rod *C*. If now a negatively charged pith ball is brought near *B*, it will be repelled, showing that *B* has become negatively charged. In this experiment the body of the experimenter corresponds to the egg *A* of the preceding experiment, and removing the finger from *B* corresponds to separating the two eggshells. Let the last experiment be repeated with only this change: that *B* is touched at *b* rather than at *a*. When *B* is again tested with the pith ball, it will still be found to have a negative charge, exactly as when the finger was touched at *a*.

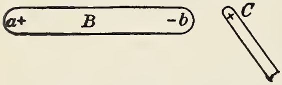


FIG. 255. A body charged by induction has a charge of sign opposite to that of the inducing charge

We conclude, therefore, that no matter where the insulated body *B* is touched, *the sign of the charge left upon it is always opposite to that of the inducing charge.* This is because the negative electricity, that is, the electrons, can under no circumstances escape from *b* so long as *C* is present, for they are *bound* by the attraction of the positive charge on *C*. Indeed, the final negative charge on *B* is due merely to the fact that the positive charge on *C* pulls electrons into *B* from the finger, no matter where *B* is touched. In the same way, if *C* had been negative, it would have pushed electrons off from *B* through the finger and thus have left *B* positively charged.

Charging the electroscope by induction. Bring an ebonite rod which has been rubbed with flannel near the knob of the electroscope. The leaves at once diverge (Fig. 256 (*a*)). Touch the knob with the

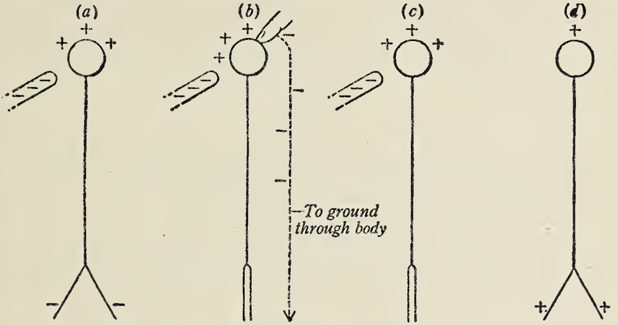


FIG. 256. Charging the electroscope by induction

finger while the rod is held in place. The leaves will fall together (Fig. 256 (*b*)). Remove the finger (Fig. 256 (*c*)), and then the rod The leaves will fly apart again (Fig. 256 (*d*)).

The electroscope is now charged by induction; and as the charge on the ebonite rod is −, the charge on the electroscope must be +. If this conclusion is tested by bringing the charged ebonite rod near the electroscope, the leaves will fall together as the rod approaches the knob. This proves that the charge on the electroscope is +. If the empty neutral hand approaches the knob, the leaves will fall. Explain.

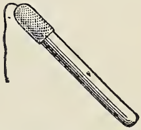


FIG. 257. Plus and minus electricities always developed in equal amounts

Plus and minus electricities always appear simultaneously and in equal amounts. Completely discharge an ebonite rod by passing it quickly through a Bunsen flame. Slip a flannel cap having a silk thread attached over the rod, as in Fig. 257, and twist it rapidly round a number of times. When rod and cap together are held near a charged electroscope, no effect will be observed; but if the cap is pulled off, it will be found to be positive, and the rod will be found to be negative.

Since the two together produce no effect, the experiment shows that the plus and minus charges were equal in amount. This experiment confirms the view already brought forward in connection with induction, that *electrification always consists in a separation of plus and minus charges that already exist in equal amounts within the bodies in which the electrification is developed.*

Summary. **Like electrical charges repel; unlike charges attract.**

A unit charge of electricity is that charge which at a distance of 1 centimeter from an exactly equal and similar charge repels it with a force of 1 dyne.

A neutral body contains equal amounts of + and − electricity.

To charge a body positively (+) some of the negative electrons of the body must be removed from it; the more, the greater the + charge.

To charge a body negatively (−) negative electrons from some other body must be added to it; the more, the greater the − charge.

When a body is charged by induction it always receives a charge opposite to that on the charging body.

Whenever a charge of electricity is developed on one body, an equal but opposite quantity is developed on some other body.

QUESTIONS AND PROBLEMS

A

1. A pith ball is covered with gold leaf and suspended by a silk thread. While a + glass rod is held near it, the pith ball exhibits a tendency to move toward the rod. Make a diagram to show the electrical condition of the bodies concerned.

2. Why is the pith ball attracted rather than repelled?

3. Why is repulsion between an unknown body and an electrified pith ball a surer sign that the unknown body is electrified than is attraction?

4. As a + rod approached a negatively charged electroscope the leaves came together; but as the + rod came still closer, the leaves diverged again. Explain.

5. If you charge an electroscope and then bring your hand toward the knob (not touching it), the leaves go closer together. Why?

6. Given a gold-leaf electroscope, a glass rod, and a piece of silk. how, in general, would you proceed to test the sign of the electrification of an unknown charge?

7. By aid of a series of diagrams explain all the steps in charging an electroscope by induction with a + glass rod.

8. State as many differences as you can between the phenomena of magnetism and those of electricity.

B

1. In the case of the rod attracting the pith ball after electrostatic induction, do you see anything analogous to a magnet attracting a nail after magnetic induction? Explain the attraction, using diagrams for both cases.

2. Trucks for the delivering of gasoline constantly dangle a chain on the ground. Why?

3. Two small spheres are charged with + 16 and − 4 units of electricity. With what force will they attract each other when at a distance of 4 cm?

4. If you bring a positively charged glass rod near the knob of an electroscope and then touch the knob with your finger, why do you not remove the negative electricity which is on the knob?

5. Charge a gold-leaf electroscope by induction from a glass rod. Warm a piece of paper and stroke it on the clothing. Hold it over the charged electroscope. (*a*) If the divergence of the gold leaves is increased, is the charge on the paper + or − ? (*b*) If the divergence is decreased, what is the sign of the charge on the paper?

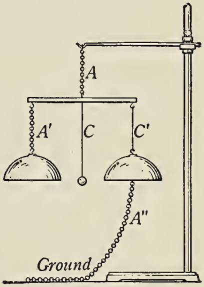


FIG. 258

6. Support the apparatus shown in Fig. 258 and connect it with one of the terminals of a static machine. C and C' are silk threads; A, A', and A'' are brass chains. Why do the bells ring when the machine is in operation?

7. If you are given a positively charged insulated sphere, how could you charge two other spheres, one positively and the other negatively, without diminishing the charge on the first sphere?

8. If you hold a brass rod in the hand and rub it with silk, the rod will show no sign of electrification; but if you hold the brass rod with a piece of sheet rubber and then rub it with silk, you will find it electrified. Explain.

Distribution of Electrical Charge upon Conductors

Electrical charges are found only upon the outside surface of conductors. Place a deep tin cup (Fig. 259) upon an insulating stand and charge it as strongly as possible either from an ebonite rod or from an electric machine. If now a smooth metal ball suspended by a silk thread is touched to the *outside* of the charged cup and then brought near the knob of a charged electroscope, it will show a strong charge; but if it is touched to the *inside* of the cup, it will show no charge at all.

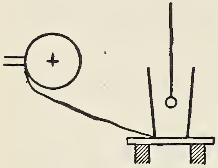


FIG. 259. Proof that charge resides on surface

This experiment shows that *an electrical charge is found entirely on the outside surface of a conductor.* We might have expected this from the fact that all the little electrical charges of which the total charge is made up repel each other and therefore move through the conductor until they are, on the average, as far apart as possible.

Density of charge greatest where curvature of surface is greatest. Since all the parts of an electrical charge tend, because of their mutual repulsions, to get as far apart as possible, we infer that if a charge of either sign is placed upon an oblong conductor like that of Fig. 260(*a*) it will distribute itself so that the electrification at the ends will be stronger than that at the middle.

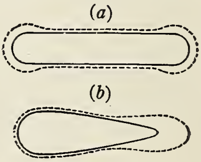


FIG. 260. Distribution of charge over oblong bodies

To test this inference touch a proof plane — a flat metal disk (for example, a cent) provided with an insulating handle — to one end of such a charged body, convey the charge to a gold-leaf electroscope,

and note the amount of separation of the leaves. Then repeat the experiment when the proof plane touches the middle of the body. The separation of the leaves in the latter case will be found to be very much less than in the former. If we should test the distribution on a pear-shaped body (Fig. 260 (*b*)) in the same way, we should find the density of electrification considerably greater on the small end than on the large one. By density of electrification is meant the quantity of electricity on each unit area of the surface.

Discharging effect of points. The foregoing experiments indicate that if one end of a pear-shaped body is made more and more pointed, then, when the body is charged, the electrical density on this end will become greater and greater. The following experiment will show what happens when the conductor is provided with a sharp point:

Attach a very sharp needle to any smooth insulated metal body provided with paper or pith-ball indicators, as in Fig. 253 (p. 316). If the body is now charged either with a rubbed rod or with an electric machine, as soon as the supply of electricity is stopped the paper indicators will immediately fall, showing that the body is losing its charge. To show that this is certainly due to the effect of the point, remove the needle and repeat. The indicators will fall very slowly if at all.

The experiment shows that the electrical density on the point is so great that the charge escapes from it into the air. This is because the intense charge on the point causes many of the adjacent molecules of the air to lose an electron. This leaves these molecules positively charged. The free electrons attach themselves to neutral molecules, thus charging them negatively. One set of these electrically charged molecules (called *ions*) is attracted to the point and the other is repelled from it. The former set move to the conductor, give up their charges to it, and thus neutralize the charge on it.

The effect of points may be shown equally well by charging the gold-leaf electroscope and holding a needle in the hand within a few inches of the knob. The leaves will fall together rapidly. In this case the needle point becomes electrified by induction and discharges to the knob electricity of the opposite kind to that on the knob,

thus neutralizing its charge. An entertaining variation of the last experiment is to attach a tassel of tissue paper to an insulated conductor and electrify it strongly. The paper streamers will under their mutual repulsions stand out in all directions; but as soon as a needle point is held in the hand near them, they will fall together (Fig. 261), being discharged as described above.

The electric whirl. Balance an electric whirl (Fig. 262) upon a pin point and attach it to one knob of an electrical machine. As soon as the machine is started, the whirl will rotate rapidly in the direction of the arrows.

The explanation is as follows: The air close to each point is *ionized*, as explained above. The ions of sign unlike that of the charge on the point are drawn to the point and discharged.

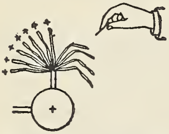


FIG. 261. Discharging effects of points

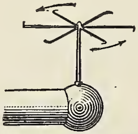


FIG. 262. The electric whirl

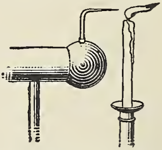


FIG. 263. The electric wind

The other set of ions is repelled. But since this repulsion is mutual, the point is pushed back with the same force with which these ions are pushed forward; hence the rotation. The repelled ions in their turn drag the air with them in their forward motions and thus produce the *electric wind*, which may be detected easily by the hand or by a candle flame (Fig. 263).

Lightning and lightning rods. In 1752, during a thunderstorm, Franklin sent up his historic kite. (See the opposite page.) This kite was provided with a pointed wire at the top. As soon as the hempen kite-string had become wet, Franklin succeeded in drawing ordinary electric sparks from a key attached to the lower end. This experiment demonstrated for the first time that thunderclouds carry ordinary electrical charges which may be drawn from them by points, just as the charge was drawn from the tassel in the experi-

Franklin's Kite Experiment

In June, 1752, Franklin demonstrated the identity of the electric spark and lightning. To prevent his kite from being torn in the rain he made it of a silk handkerchief. The lower end of the kite string and a silk ribbon were tied to the ring of a key, and, to prevent any charge that might appear upon the string and the key from escaping through his body to the earth, he held the kite by grasping the insulating silk ribbon. Standing under a shed to keep the ribbon dry, Franklin, by presenting his knuckle to the key, obtained sparks similar to those produced by his electric machine. With these sparks he charged his Leyden jar and used it to give a shock. Indeed, he performed all the experiments which he had previously performed with sparks from his frictional machine. (Dangerous! Do not repeat!)

Dr. K. Winfield Ney

When Lightning Strikes a Skyscraper

Since Franklin, lightning has had no terrors for those inside a steel-framed building or any other grounded conducting framework. The Empire State Building did not know it when the lightning struck

ment of Fig. 261. It also showed that lightning is nothing but a huge electric spark (see opposite pages 325 and 328). Franklin applied this discovery in the invention of the lightning rod. The way in which the rod discharges the cloud and protects the building is as follows: As the charged cloud approaches the building, it induces an opposite charge in the rod. This induced charge escapes rapidly and quietly from the sharp point in the manner explained above, thus neutralizing the charge of the cloud.

To illustrate, support a metal plate *C* (Fig. 264) above a metal ball *E*, and let *C* and *E* be attached to the two knobs of an electric machine. When the machine is started, sparks will pass from *C* to *E*. But if a point *p* is connected to *E*, the sparking will cease; that is, the point will protect *E* from the discharges, even though the distance *Cp* be considerably greater than *CE*.

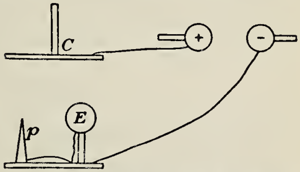


FIG. 264. Illustrating the action of a lightning rod

In many cases the quantity of electricity in the clouds is so huge that this process of silent discharge is not rapid enough to prevent the actual lightning stroke. Of course, when this happens, the rod protects simply by furnishing a metallic channel through which the lightning may pass to earth. The rod must obviously be properly insulated from the building.

Flashes of lightning over a mile long have often been observed (see the opposite page). Thunder is due to violent expansion of heated air along the path of discharge. The roll of thunder is due to reflections of sound from clouds, hills, etc.*

Summary. **An electrical charge resides on the outside of a conductor because of the mutual repulsion of the like parts of the charge.**

The electrical density of a charge is greatest on sharp curves; on points it is so great that the adjacent air becomes ionized.

A laboratory exercise on static electrical effects should follow the discussion of this section. See, for example, Experiment 33 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

The discharging effect of points is due to the conducting power of ionized air in the vicinity of the point.

Lightning rods owe their usefulness to the discharging effects of their points.

QUESTIONS AND PROBLEMS

1. Will a solid sphere hold a larger charge of electricity than a hollow one of the same diameter?

2. Represent by a drawing the electrical condition of a tower just before it is struck by lightning, assuming the cloud at this particular time to be powerfully charged with + electricity.

3. When a negatively electrified cloud passes over a house provided with a lightning rod, the charged points ionize the air, and the charged cloud is thereby rendered less dangerous. Explain.

Potential and Capacity

Potential difference. There is a very helpful analogy between the use of the word *potential* in the study of electricity and *pressure* in the study of liquids. For example, if water will flow from tank A to tank B through the connecting pipe R (Fig. 265), we infer that the pressure of the water at a must be greater than that at b, and we think of the flow as due to this difference in pressure. In exactly the same way, if, when two bodies A and B (Fig. 266) are connected by a conducting wire r, a charge of + electricity is found to pass from A to B (that is, if electrons are found to pass from B to A), we say that the electrical potential is higher at A than at B, and we take this *difference of potential* as the cause of the flow.* Thus, just as water tends to flow from

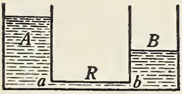


FIG. 265. Illustrating hydrostatic pressure

* Franklin thought that it was the positive electricity which moved through a conductor, and he conceived the negative as inseparably associated with the atoms. Hence it became a universally recognized convention to regard electricity as moving through a conductor in the direction in which a + charge would have to move in order to produce the observed effect. It is not desirable to attempt to change this convention now, even though the electron theory has exactly inverted the roles of the + and − charges.

points of higher hydrostatic pressure to points of lower hydrostatic pressure, so electricity tends to flow from points of higher electrical pressure, or potential, to points of lower electrical pressure, or potential.

Again, if water is not continuously supplied to one of the tanks *A* or *B* of Fig. 265, we know that the pressures at *a* and *b* must soon become the same. Similarly, if no electricity is supplied to the bodies *A* and *B* of Fig. 266, their potentials very quickly become the same. In other words, *all points on a system of connected conductors in which the electricity is in a stationary, or static, condition are at the same potential.* This result follows at once from the fact that electrical charges are free to move through conductors.

Fig. 266. Illustrating electrical pressure

But if water is continuously poured into *A* and removed from *B* (Fig. 265), the pressure at *a* will remain permanently above the pressure at *b*, and a continuous flow of water will take place through *R*. So if *A* (Fig. 266) is connected with an electric machine and *B* to earth, a permanent potential difference will exist between *A* and *B*, and a continuous current of electricity will flow through *r*. Difference in potential is commonly denoted simply by the letters P.D. (Potential Difference).

Some methods of measuring potentials. The simplest and most direct way of measuring the potential difference between two bodies is to connect one to the knob, the other to the conducting case,* of an electroscope. The amount of separation of the gold leaves is a measure of the P.D. between the bodies. The unit in which P.D. is usually expressed is called the *volt.* It will be accurately defined on page 373. It will be sufficient here to say that it is approximately equal to the electrical pressure between the ends of copper and

* If the case is of glass, it should always be made conducting by pasting tinfoil strips on the inside of the jar opposite the leaves and extending these strips over the edge of the jar and down on the outside to the conducting support on which the electroscope rests. The object of this is to maintain the walls always at the potential of the earth.

zinc strips when dipped in dilute sulfuric acid or to two thirds of the electrical pressure between the zinc and carbon terminals of the familiar dry cell.

Since the earth is, on the whole, a good conductor, its potential is everywhere the same (p. 327); hence it makes a convenient standard of reference in potential measurements. To find the potential of a body relative to that of the earth, we connect the outer case of the electroscope to the earth by means of a wire and connect the body to the knob. If the electroscope is calibrated in volts, its reading gives the P.D. between the body and the earth. Such calibrated electroscopes are called *electrostatic voltmeters*. They are the simplest and in many respects the most satisfactory forms of voltmeters to be had. Their use, both in laboratories and in electrical-power plants, is rapidly increasing. They can be made to measure a P.D. as small as $\frac{1}{1000}$ volt and as large as 200,000 volts. Fig. 267 shows one of the simpler forms. The outer case is of metal and is connected to earth at the point *a*. The body whose potential is sought is connected to the knob *b*. This is in metallic contact with the light aluminum vane *c*, which takes the place of the gold leaf.

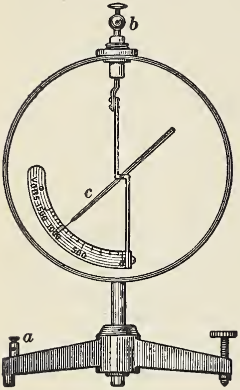


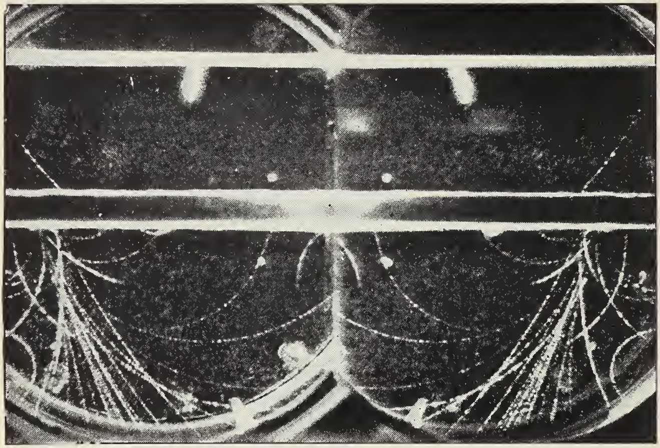
FIG. 267. Electrostatic voltmeter

A very convenient way of measuring a *large* P.D. without a voltmeter is to measure the length of the longest spark that will pass between the two bodies whose P.D. is sought. The P.D. is roughly proportional to spark length, each centimeter of spark length representing a P.D. of about 30,000 volts if the electrodes are large compared with their distance apart.

Condensers. Mount a metal plate *A* on an insulating base and connect it with an electroscope, as in Fig. 268. Mount a second plate *B* similarly and connect it to earth by a conducting wire.

A 35-Foot Electrical Discharge

This huge discharge passes from the transformer terminal to the grounded frame of the steel building. These transformers develop 1,000,000 volts at 1000 kilowatts



Photograph of a 3,000,000,000-Volt Cosmic-Ray Shower

Up to 1931 the highest potential differences that man had been able to produce and to measure on earth were of the order of 1,000,000 volts, a very few million at most. The energy which an electron acquires in falling through a P.D. of 1 volt is called an electron volt. Radioactive substances (Chap. XXI) shoot out electrically charged particles that have energies of the order of 10,000,000 electron volts, and these were the highest charged-particle energies known to exist up to 1931. In that year it was photographically proved, however, that the earth is continuously being bombarded by cosmic-ray bullets, — photons or electrons or both, — coming from beyond the Milky Way, of enormously higher energies than any found on earth. Such a cosmic ray, plunging through the lead bar 1 centimeter thick shown in the middle of the picture, collides head on in the middle of the bar with the nucleus of a lead atom. Fifteen positive electrons (Chap. XXIII), tracks curving to the right in the left-hand photograph (the other is merely a mirror image taken for stereoscopic purposes), and ten negative electrons, the tracks curving to the left, emerge from the collision with a joint measured energy of more than 3,000,000,000 electron volts, so that the cosmic ray that entered the lead from above — here almost certainly a photon (Chap. XXIII), since it does not ionize above the lead — must have possessed at least 3,000,000,000 electron volts of energy. Cosmic-ray tracks of energies up to 10,000,000,000 electron volts have thus been definitely measured

Charge A and note the deflection of the gold leaves. If now we push B toward A, we observe that, as it comes near, the leaves begin to fall together, showing that the potential of A is diminished by the presence of B, although the quantity of electricity on A has remained unchanged. If we convey additional − charges to A with the aid of a proof plane, we shall find that many times the original amount of electricity may now be put on A before the leaves return to their original divergence, that is, before the body regains its original potential.

We say, therefore, that the *capacity* of A for holding electricity has been very greatly increased by bringing near it another conductor connected to earth. It is evident from this statement that *we measure the capacity of a body by the amount of electricity which must be put upon it to raise the potential a given amount.* The explanation of the increase in capacity in this case is obvious. As soon as B was brought near to A it became charged, by induction, with electricity of opposite sign to A, the electricity of like sign to A being driven off to earth through the connecting wire. The attraction between these opposite charges on A and B drew the electricity on A to the face nearest to B and removed it from the more remote parts of A, so that it became possible to put a very much larger charge on A before the tendency of the electricity on A to pass over to the electroscope became as great as it was at first, that is, before the potential of A rose to its initial value. In such a condition the electricity on A is said to be *bound* by the opposite electricity on B.

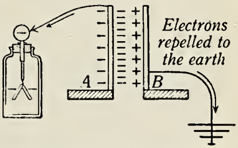


FIG. 268. The principle of the condenser

An arrangement of this sort consisting of two conductors separated by a nonconductor is called a condenser. If the conducting plates are very close together and one of them is grounded, the capacity of the system may be thousands of times as great as that of one of the plates alone.

The Leyden jar. The most common form of condenser is a glass jar coated part way to the top inside and outside with

tin foil (Fig. 269). The inside coating is connected by a chain to the knob, and the outside coating is connected to earth. Condensers of this sort first came into use in Leiden (or Leyden), Holland, in 1745. Hence they are now called *Leyden jars.*

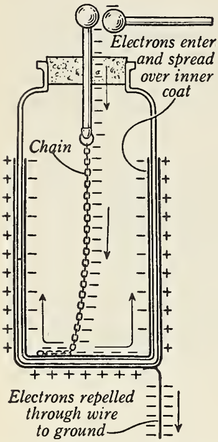


FIG. 269. The Leyden jar

To charge a Leyden jar the outer coating is held in the hand while the knob is brought into contact with one terminal of an electric machine — for example, the negative. As fast as electrons pass to the knob, they spread to the inner coat of the jar, where they repel electrons from the outer coat to the earth, thus leaving it positively charged. If the inner and outer coatings are now connected by a discharging rod, as in Fig. 274, a powerful spark will be produced. This spark is due to the rush of electrons from the − coat to the + coat. Place a charged jar on a glass plate so as to insulate the outer coat. Touch the knob with the finger; no appreciable discharge will be noticed. Touch the outer coat in turn with the finger; again no appreciable discharge will appear. But if the inner and outer coatings are connected by the discharger, a powerful spark will pass.

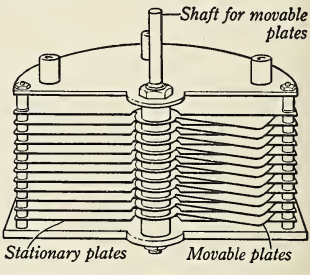


FIG. 270. A variable radio condenser

Such an experiment shows that it is impossible to discharge one side of the jar alone, for practically all the charge is held in place by the opposite charge on the other coat. The full discharge can therefore occur only when the inner and outer coats are connected.

Leyden jars and other forms of condensers are of great practical use. They are used, for instance, in certain systems of telephony and telegraphy, in radio communication, and in electrostatic machines and induction coils. Fig. 270 shows a variable radio condenser. Its capacity is changed by rotating the movable leaves so that they penetrate a greater or less amount between the stationary leaves, thus in effect varying the size of the condenser plates.

The electrophorus. The electrophorus, a simple electric generator invented by Volta in 1777, illustrates well the principle underlying the action of all electrostatic machines. All such machines generate electricity primarily by induction, not by friction. *A* (Fig. 271) is a hard-rubber plate which is first charged by rubbing it with fur or flannel. *B* is a metal plate provided with an insulating handle. When the plate *B* is placed upon *A*, touched with the finger, and then removed, it is found possible to draw a spark from it, which in dry weather may be a quarter of an inch or more in length. The process may be repeated an indefinite number of times without diminishing the size of the spark which may be drawn from *B*.

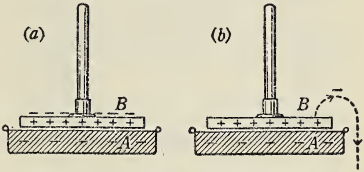


FIG. 271. Charging an electrophorus

If the sign of the charge on *B* is tested by means of an electroscope, it will be found to be positive. This proves that *B* has been charged by induction, not by contact with *A*, for it is to be remembered that the latter is charged negatively. The reason for this is that even when *B* rests upon *A* it is in reality separated from it, at all but a very few points, by an insulating layer of air; and since *A* is a nonconductor, it cannot appreciably lose its charge by way of these few points of contact. It simply repels negative electrons to the top side of the metal plate *B* and thus charges positively the lower side. These electrons pass off to earth when the plate is

touched with the finger. Hence, when the finger is removed and B is lifted, it possesses a strong positive charge. Every commercial electrostatic machine works simply as a continuously acting electrophorus which generates electricity by induction, not by friction.

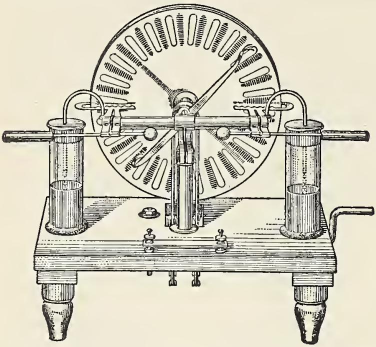


FIG. 272. The Wimshurst induction machine

The Wimshurst electric machine. The ordinary static machine is nothing but a continuously acting electrophorus. Fig. 272 represents the Wimshurst electric machine. It has two plates revolving in opposite directions, and these plates carry a large number of tin-foil strips which act alternately as inductors and as carriers. The action of the machine may be understood readily from Fig. 273. Suppose that a small negative charge is placed on a. This, acting inductively on the rod rs, charges a' positively. When a' in the course of the rotation reaches the position b', it acts inductively on the rod $s'r'$ and thus charges the disk b negatively. It will be seen that henceforth all the disks in the inner circle receive + charges as they pass the brush r and that all the disks in the outer circle (that is, on the back plate) receive — charges as they pass the brush s'. Similarly on the lower half of the plates all the disks on the inner circle receive — charges as they pass the brush s, and all the disks on the outer circle receive + charges as they pass the brush r'.

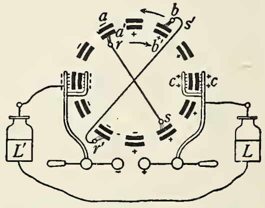


FIG. 273. Principle of Wimshurst machine

When the positive charges on the inner disks come opposite the combs c, they pass off to the + knob of the machine or to the Leyden jar connected with it. The same process is occurring on the other side, where − charges are being taken off. When a spark passes, the Leyden jars and the connecting system of conductors are restored to their initial conditions, and the process begins again.

Summary. **Potential difference bears the same relation to electrical flow as pressure difference to liquid flow.**

It may be measured (1) by a calibrated electroscope or electrostatic voltmeter or (2) by the length of the spark discharge.

A condenser consists of two conductors that are separated by a nonconductor.

The capacity of a condenser is the ratio between its charge and the potential difference between its plates.

The electrophorus and the Wimshurst machine are electrostatic generators which depend for their action upon electrostatic induction.

QUESTIONS AND PROBLEMS

1. Why cannot a Leyden jar be appreciably charged if the outer coat is insulated?

2. Explain, using a set of drawings, the charging of the cover of an electrophorus.

3. Why is the capacity of a conductor greater when another conductor connected to the earth is near it than when it stands alone?

4. Is the continued use of the electrophorus an example of perpetual motion? If not, what is the source of energy?

5. By reference to Fig. 273 explain how a Wimshurst machine builds up a large + charge in one jar and a correspondingly large − charge in the other.

CHAPTER XIV

Electricity in Motion*

Detection of Electric Currents

Electricity in motion produces a magnetic effect. Place an unmagnetized steel knitting needle in a piece of glass tubing and wrap a coil of wire around the tubing. Connect one end of the wire to the outside of a charged Leyden jar; then touch the knob of the jar with the other end of the wire, noting the effect on a compass needle at rest, as shown in Fig. 274. The jar discharges through the coil, which is insulated from the knitting needle by the glass. The needle will be found, by the action of the compass, to be distinctly magnetized by the discharge.

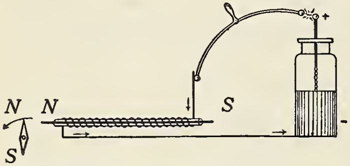
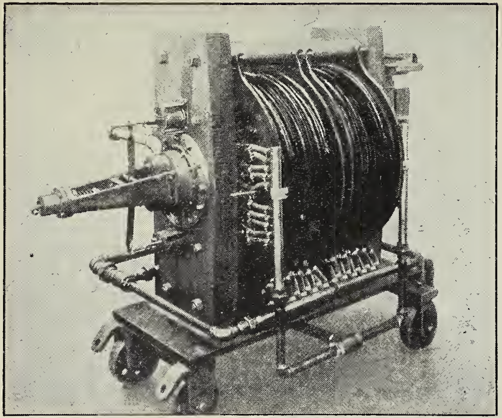


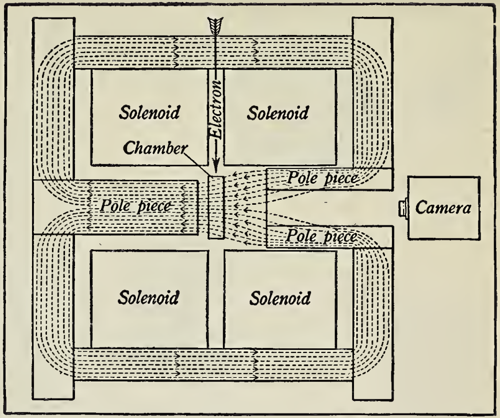
FIG. 274. Magnetic effect of an electric current produced from a static charge

The experiment shows that there is a definite connection between electricity and magnetism. Just what this connection is we do not yet know with certainty, but we do know that magnetic effects may always be detected near the path of a moving electrical charge, whereas no such effects can ever be observed near a charge at rest.

Bring a charged body near a compass needle. It will attract either end of the needle with equal readiness. While the needle is deflected, place between it and the charge a sheet of zinc, aluminum, brass, or copper. This will act as an electrical screen; that is, it will cut off all effect of the charge. The compass needle will at once swing back to its north-and-south position.

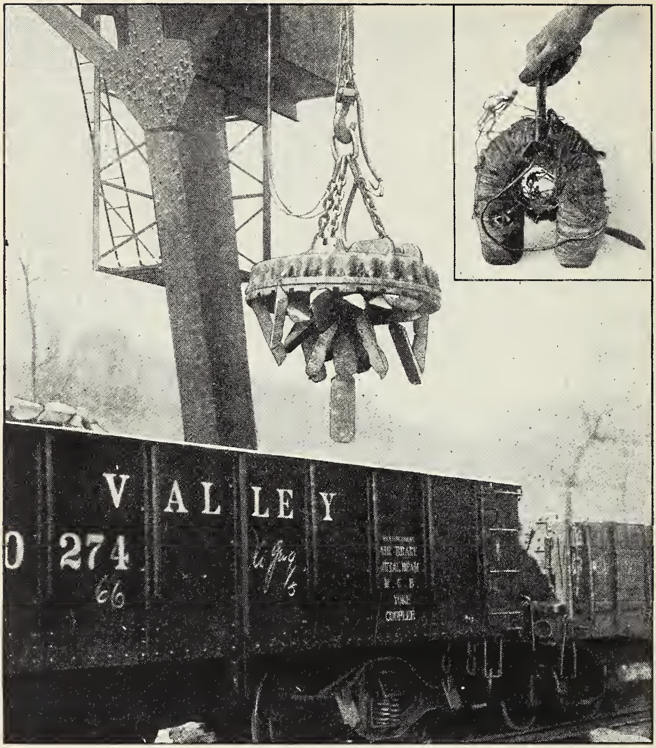
* This chapter should be accompanied or, better, *preceded* by laboratory experiments on the simple cell and on the magnetic effects of a current. See, for example, Experiments 34, 36, 37, and 38 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.





Extending the Measurement of Electrically Charged "Bullets" from 10,000,000 to 10,000,000,000 Electron Volts

This is the exceedingly powerful electromagnet built (1931) by Carl D. Anderson with which the energies of the cosmic rays (see opposite pages 329 and 375) were first directly measured. Electrons plunge from above through the cloud "chamber" (see diagram at right, and page 610), trigger the "camera," and take their own photographs. As the apparatus is used, the tracks are deflected to the left (in the left-hand image opposite page 329) if the electrons are negative, to the right if positive; and by the amount of this curvature we determine their energy. The magnetic field passing through the chamber is produced by a current of 2000 amperes passing through the solenoid. (See diagram at right.) It is essentially uniform and has the huge intensity of 24,000 units (gausses) throughout the whole volume of the cylindrical chamber, which is 17 centimeters in diameter (from top to bottom). It is a simple application of Oersted's discovery of the effect of an electric current in creating a magnetic field around it



Electromagnets

This page shows in the upper right-hand corner a photograph of the first electromagnet. It was constructed at Princeton in 1828 by Joseph Henry. He wound the arms of a U-shaped piece of iron with several layers of wire insulated by wrapping around it strips of silk. The main illustration is a huge, modern lifting magnet, which itself weighs 8720 pounds, is 5 feet 2 inches in diameter, and can lift a single flat piece of iron weighing 70,000 pounds. It has 118,000 ampere turns, and carries 84 amperes at 220 volts. The coil is built up of several pancakes of copper straps, the turns of strap being insulated from one another by asbestos ribbon wound between them. The magnet is loading a freight car with pig iron, of which its average lift is 4000 pounds

Deflect the compass needle by a bar magnet, and put the screen in again. The sheet of metal does not cut off the magnetic forces in the slightest degree.

The fact that an electrical charge at rest exerts no magnetic force is shown, then, both by the fact that it attracts either end of the compass needle with equal readiness and by the fact that the screen cuts off its action completely, whereas the same screen does not have any effect in cutting off the magnetic force.

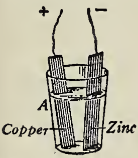


FIG. 275. Simple voltaic cell

An electrical charge in motion is called an electric current, and its presence is most commonly detected by the magnetic effect which it produces. A current of electricity is generally a stream of negative electrons. (See Franklin's conception in the footnote on page 326.)

The galvanic cell. When a Leyden jar is discharged, only a very small quantity of electricity passes through the connecting wires, since the current lasts for only perhaps a millionth of a second. If we could keep a current flowing continuously through the wire, we should expect the magnetic effect to be much greater. In 1786 Galvani, an Italian anatomist at the University of Bologna, accidentally discovered that there is a chemical method for producing such a continuous current. His discovery was not understood, however, until Volta, while trying to throw light upon it, in 1800 invented an arrangement which is now known sometimes as the *voltaic* and sometimes as the *galvanic* cell. This consists, in its simplest form, of a strip of copper and a strip of zinc immersed in dilute sulfuric acid (Fig. 275).

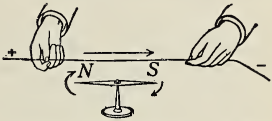


FIG. 276. Oersted's experiment

Connect the terminals of such a cell for a few seconds to the ends of the coil of Fig. 274 when an unmagnetized needle lies within the glass tube. The needle will become magnetized. Again, hold the wire which connects the terminals of the cell above a compass needle, as in Fig. 276; the needle will be strongly deflected.

Evidently, then, the wire which connects the terminals of a galvanic cell carries a current of electricity. Historically the second of these experiments, performed by the Danish physicist Oersted in 1820, was made before the discovery of the magnetizing effects of currents upon needles. It created a great deal of excitement at the time, because it was the first clue which had been found to a relationship between electricity and magnetism.

FIG. 277. Hans Christian Oersted (1775–1851), the discoverer of the connection between electricity and magnetism

Plates of a galvanic cell are electrically charged. Since an electric current flows through a wire as soon as it is touched to the zinc and copper strips of a galvanic cell, we at once infer that the terminals of such a cell are electrically charged before they are connected. That this is indeed the case may be shown as follows:

Place a metal plate *A* (Fig. 278), covered with shellac (a nonconductor) on its lower side and provided with an insulating handle, upon a similar plate *B* which is in contact with the knob of an electroscope. Connect the copper plate of a galvanic cell or series of cells with *A* and the zinc plate with *B*, as in Fig. 278. Then remove the connecting wires and lift the plate *A* away from *B*. The opposite electrical charges which were bound by their mutual attractions to the adjacent faces of *A* and *B*, so long as these faces were separated only by the thin coat of shellac, are freed as soon as *A* is lifted, and hence part of the charge on *B* passes to the leaves of the electroscope. The leaves will diverge. If a negative charge is brought near the electroscope, the leaves will diverge still farther, showing that the zinc plate of the cell is negatively charged. If the experiment is repeated with the copper plate in contact with *B* and the zinc in contact with *A*, the leaves will be found to be positively charged.*

* If the deflection of the gold leaves is too small for purposes of demonstration, let a battery of from five to ten cells be used instead of the single cell. If, however, the plates *A* and *B* are 3 or 4 inches in diameter and very flat, one cell will do.

The terminals of a galvanic cell therefore carry positive and negative charges just as do the terminals of an electric machine in operation. The + charge is always found upon the copper and the − charge upon the zinc. The source of these charges is the chemical action which takes place within the cell. When these terminals are connected by a conductor, a current flows through the latter just as in the case of the electric machine. It is the universal custom to consider that a current flows from the positive terminal of a *generator*, or *source* of current, through the external circuit to the negative terminal, that is, in this case, from copper to zinc outside the cell.

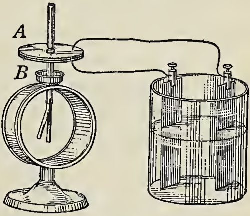


FIG. 278. Showing charges on plates of a voltaic cell

Comparison of a galvanic cell and a static machine. If one knob of a static machine in operation were touched to the knob of a gold-leaf electroscope, the leaves would fly apart so violently that they would probably be torn from each other; but if one of the terminals of a galvanic cell is touched to the electroscope directly without the use of the condenser plates *A* and *B* of Fig. 278, no noticeable divergence of the leaves will be detected. Since we have seen (p. 328) that the divergence of the gold leaves is a measure of the potential of the body to which they are connected, this experiment shows us that the static machine produces a high potential between its terminals, whereas the potential which the chemical action of the galvanic cell is able to produce is so small that it cannot spread the leaves enough to be noticeable. As a matter of fact, the potential difference between the terminals of the cell is about 1 volt, whereas that between the knobs of the electrical machine may be as much as 200,000 volts.

But if the knobs of the static machine are connected to the ends of the wire of Fig. 276, and the machine operated, the current sent through the wire will not be large enough to produce any appreciable effect upon the needle. Since under

these same circumstances the galvanic cell produced a very large effect upon the needle, we learn that although the cell develops a very small P.D. between its terminals, it nevertheless sends through the connecting wire very much more electricity per second than the static machine is able to send. This is because the chemical action of the cell is able to recharge the plates to their small P.D. practically as fast as they are discharged through the wire, whereas the static machine requires a relatively long time to recharge its terminals to their high P.D. after they have once been discharged.

Summary. **An electrical charge in motion creates a magnetic field about the conductor carrying it.**

A galvanic cell, like a static machine, develops + and − charges upon its terminals. The former produces large currents at small potentials; the latter, small currents at high potentials.

QUESTIONS AND PROBLEMS

1. Under what conditions will an electrical charge produce a magnetic effect?

2. How can you test whether or not a current is flowing in a wire?

3. How does the current delivered by a cell differ from that delivered by a static machine?

4. Mention (*a*) three respects in which the behavior of magnets is similar to that of electrical charges; (*b*) two respects in which it is different.

*Chemical Effects of the Current; Electrolysis**

Electrolysis. Connect two platinum strips to the terminals of a battery producing 10 volts or more, and dip them into a dilute solution of sulfuric acid, as in Fig. 279. Such metal terminals in a solution are called *electrodes*. Oxygen gas is found to be given off at the electrode at which the current enters the solution, called the *anode* (+), and hydrogen is given off at the electrode at which the current leaves the solution, called the *cathode* (−). These gases may be collected in test tubes in the manner shown in Fig. 280.

* This subject should be accompanied or followed by a laboratory experiment on electrolysis and the principle of the storage battery. See, for example, Experiments 35 and 44 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

When sulfuric acid is mixed with so much water that it forms a dilute solution, the H_2SO_4 molecules split up into three electrically charged parts, called *ions*. An ion may be defined as an atom or group of atoms carrying an electrical charge. Two hydrogen ions each carry a positive charge and the SO_4 ion carries a double negative charge (Fig. 281). This phenomenon is known as *dissociation*. The solution as a whole is neutral; that is, it is uncharged, because it contains just as many positive as negative charges.

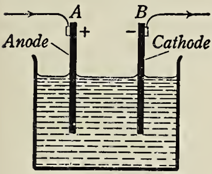


FIG. 279. Electrolytic cell

As soon as an electrical field is established in the solution by connecting the electrodes to the positive and negative terminals of a battery, the positive hydrogen ions begin to move toward the negative electrode (that is, the cathode) and there, after giving up their charges, unite two and two to form molecules of hydrogen gas (Fig. 281). What actually happens is that the positive hydrogen ion "steals" a negative electron from the plate. Since a negative current going one way is equivalent to a positive current going the other, this whole process is the equivalent of the giving up by the ion of its positive charge to the plate, and that is the usual way in which we describe it. The negative SO_4 ions move to the positive electrode (that is, the anode), where they give up their charges to it and then combine with the H_2 of the water (H_2O), thus forming H_2SO_4 and liberating oxygen.

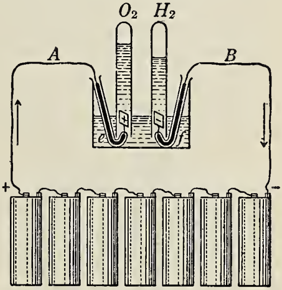


FIG. 280. Electrolysis of water

Electroplating. If the solution, instead of being sulfuric acid, had been one of copper sulfate ($CuSO_4$), the results would have been precisely the same in every respect, except

that, since the hydrogen ions in the solution are now replaced by copper ions, the substance deposited on the cathode is pure copper instead of hydrogen. This is the principle involved in electroplating of all kinds. In commercial work the positive plate, that is, the plate at which the current enters the bath, is usually made from the same metal as that which is to be deposited from the solution, for in this case the SO_4 or other negative ions dissolve this plate as fast as the metal ions are deposited upon the other. The strength of the solution, therefore, remains unchanged. In effect, the metal is simply taken from one plate and deposited on the other. Fig. 282 represents a simple form of silver-plating bath. The anode *A* is of pure silver. The spoon to be plated is the cathode *K*. In practice the articles

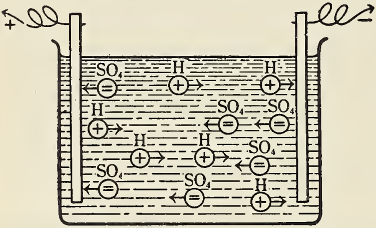


FIG. 281. Showing dissociation of sulfuric acid molecules in water

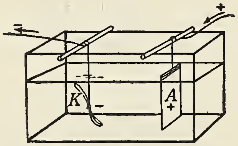


FIG. 282. A simple electro plating bath

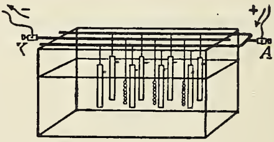


FIG. 283. Electroplating bath

to be plated are often suspended from a central rod (Fig. 283), and on both sides about the articles are the suspended anodes. This arrangement gives a more even deposit of metal. In silver plating the solution consists of 500 grams of potassium cyanide and 250 grams of silver cyanide in 10 liters of water. In a similar way metals are coated with thin layers of nickel and chromium.

Electrotyping. In the process of electrotyping, the page is first set up in the form of common type. A mold is then taken in wax or gutta-percha. This mold is then coated with powdered graphite to make it a conductor, after which it is ready to be hung as the cathode in a copper-plating bath, the anode being a plate of pure copper and the liquid a solution of copper sulfate. When a sheet of copper as thick as a visiting card has been deposited, it is removed from the mold and is backed with an alloy of lead, antimony, and tin to make a plate three twentieths of an inch thick for stiffness. From such a plate as many as a hundred thousand impressions may be made. Nearly all books which run through large editions are printed from such electrotypes.

Extraction and refining of metals. Most of the pans in your kitchen are probably made of aluminum. The large-scale use of this metal has been made possible by the discovery of a method of extracting it from its ore, bauxite (largely Al_2O_3), by electrolysis. The ore is dissolved in a molten mineral called cryolite. It separates into positive aluminum ions, which go to the cathode and are deposited, and negative oxygen ions, which move to the anode and there form oxygen gas. Other metals, such as sodium, magnesium, and potassium, are obtained by electrolysis. Copper is refined by using an impure specimen as the anode and pure copper as the cathode.

Legal units of current and quantity. In 1834 Faraday (see opposite page 392) found that the same current of electricity flowing for the same length of time always deposits the same amount of a given element from a solution, whatever be the nature of the solution which contains the element. For example, 1 ampere, the unit of current, always deposits in an hour 4.025 grams of silver, whether the electrolyte is silver nitrate, silver cyanide, or any other silver compound. This is called the *electrochemical equivalent* of silver. Similarly 1 ampere will deposit in an hour 1.181 grams of copper, 1.203 grams of zinc, etc. Faraday further found that the amount of metal deposited in a given cell depended solely

on the product of the current strength by the time, that is, on the *quantity* of electricity which had passed through the cell. (When 1 ampere flows for 1 hour, the quantity of electricity which passes is sometimes called an *ampere-hour.*) In other words, the quantity of metal deposited depends on (1) the strength of the current, (2) the length of time it flows, and (3) the electrochemical equivalent of the substance deposited. These facts are made the basis of the legal definitions of current and quantity, thus:

The unit of current, the ampere, is the current which will deposit .001118 gram of silver in 1 second.

The unit of quantity, called the coulomb, is the quantity of electricity required to deposit .001118 gram of silver.

Summary. **Electrolysis is the passage of current by the movement of ions in a solution.**

In electroplating, the anode dissolves at the same rate at which the metal is deposited from solution at the cathode.

QUESTIONS AND PROBLEMS

A

1. How is an electric current carried by an electrolyte?

2. Describe and explain the electrolysis of water, giving the chemical and electrical principles involved.

3. How could a silver cup be given a gold lining by use of the electric current? Draw a diagram and label carefully.

4. (*a*) In the electrolysis-of-water experiment why was sulfuric acid added to the water? (*b*) Why were the electrodes made out of platinum?

5. How long will it take a current of 1 ampere to deposit 1 g of silver from a solution of silver nitrate?

B

1. What current is needed to deposit 44.2 g of silver in $2\frac{1}{2}$ hr?

2. The coulomb is 3 billion times as large as the electrostatic unit of quantity defined on page 313. How many electrons pass per second by a given point on a lamp filament which is carrying 1 ampere of current? (See page 317.)

3. (*a*) How many coulombs are there in an ampere-hour?
   (*b*) How many ampere-hours are there in a coulomb?

4. Name two reasons why such a metal as iron is electroplated.

5. Upon what three things does the weight of an electroplate depend?

Magnetic Effects of the Current; Properties of Coils

Shape of the magnetic field about a current. We have already seen that electrical charges in motion produce a magnetic effect. To find out more about the nature of current

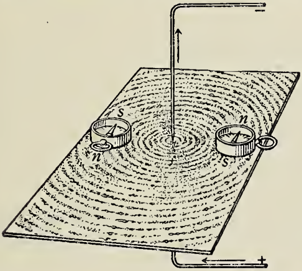


FIG. 284

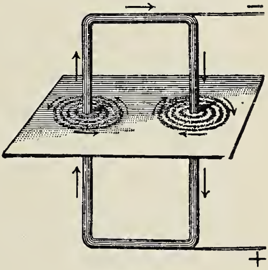


FIG. 285

Magnetic field about a current

electricity we must investigate more thoroughly by experiment just what this magnetic effect is.

If we place the wire which connects the plates of a galvanic cell in a vertical position (Fig. 284) and explore with a compass needle the shape of the magnetic field about the current, we find that the magnetic lines are concentric circles lying in a plane perpendicular to the wire and having the wire as their common center. We find, moreover, that reversing the current reverses the direction of the needle. If the current is very strong (say 40 amperes) this shape of the field can be shown by scattering iron filings on a plate through which the current passes (Fig. 284). If the current is weak, the experiment should be performed by using a large number of turns of wire, as indicated in Fig. 285.

The relation between the direction in which the current flows and the direction in which the N pole of the needle points (this is, by definition, the direction of the magnetic field) is given in the following convenient rule, known as Ampère's rule: *If the right hand grasps the wire as in Fig. 286 so that the thumb points in the direction in which the current is flowing, then the magnetic lines encircle the wire in the same direction as do the fingers of the hand.*

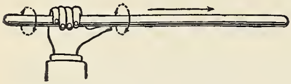


FIG. 286. The right-hand rule

Loop of wire carrying a current equivalent to a magnet disk. Suspend a single loop of wire from a thread in the manner shown in Fig. 287, so that its ends dip into two mercury cups. Then send the current from three or four dry cells through the loop. The latter will be found slowly to set itself so that the face of the loop from which the magnetic lines emerge, as given by the right-hand rule (see Fig. 286 and also Fig. 288), is toward the north. Bring a bar magnet near the loop. The latter will be found to behave toward the magnet in all respects as though it were a flat magnetic disk whose boundary is the wire, the face which turns toward the north being an N pole and the other an S pole.

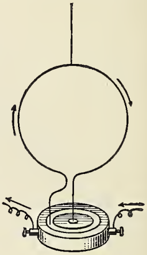


FIG. 287. A loop equivalent to a flat magnetic disk

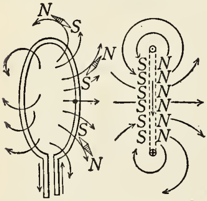


FIG. 288. North pole of disk is face from which magnetic lines emerge; south pole is face into which they enter

The experiment shows what position a loop bearing a current will always tend to assume in a magnetic field; for, since a magnet will always tend to set itself so that the line connecting its poles is parallel to the direction of the magnetic lines of the field in which it is placed, a loop must set itself so that a line connecting its magnetic poles is parallel to the lines of the magnetic field, that is, so that *the plane of the loop is perpendicular to the field* (see Fig. 289); or,

to state the same thing in slightly different form, *if a loop of wire, free to turn, is carrying a current in a magnetic field, the loop will set itself so as to include as many as possible of the lines of force of the field.*

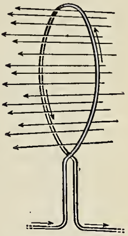


FIG. 289. Position assumed by a loop carrying a current in a magnetic field

Helix carrying a current equivalent to a bar magnet. Wind a wire bearing a current into a series of loops (a *helix*, or *solenoid*) and hold it near a suspended magnet, as in Fig. 290. It will be found to act in every respect like a magnet, with an *N* pole at one end and an *S* pole at the other.

This result might have been predicted from the fact that a single loop is equivalent to a flat-disk magnet; for when such disks are placed side by side in a series, as in the helix, the result must be the same as placing a series of disk magnets in a row, the *N* pole of one being directly in contact with the *S* pole of the next, etc. These poles would therefore all neutralize each other except at the two ends. We therefore get a magnetic field of the shape shown in Fig. 291, the direction of the arrows representing as usual the direction in which an *N* pole tends to move.

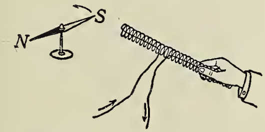


FIG. 290. Magnetic effect of a helix

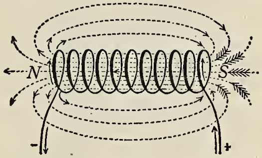


FIG. 291. Magnetic field of helix

The right-hand rule as given on page 344 is sufficient in every case to determine which is the *N* and which the *S* pole of a helix, that is, from which end the lines of magnetic force emerge from the helix and at which end they enter it. But it is found convenient, in the consideration of coils, to restate the right-hand rule in a slightly different way, thus: *If the*

coil is grasped in the right hand in such a way that the fingers point in the direction in which the current is flowing in the wires, the thumb will point in the direction of the north pole of the helix. (See Fig. 292.)

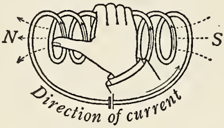


FIG. 292. Rule for poles of helix

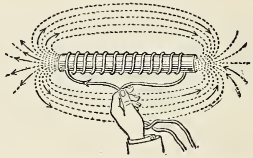


FIG. 293. The bar electromagnet

The electromagnet. Insert a core of soft iron in the helix (Fig. 293). The poles will be found to be enormously stronger than before. This is because the core is magnetized by induction from the field of the helix in precisely the same way in which it would be magnetized by induction if placed in the field of a permanent magnet. The new field strength about the coil is now the sum of the field due to the core and that due to the coil. If the current is broken, the core will at once lose the greater part of its magnetism. If the current is reversed, the polarity of the core will be reversed. Such a coil with a soft-iron core is called an *electromagnet.*

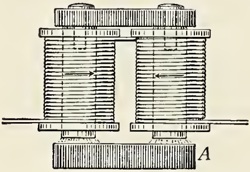


FIG. 294. The horseshoe electromagnet

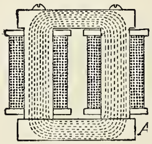


FIG. 295. The magnetic circuit of an electromagnet

The strength of an electromagnet can be very greatly increased by giving it such form that the magnetic lines can remain in iron throughout their entire length instead of emerging into air, as they do in Fig. 293. For this reason electromagnets are usually built in the horseshoe form and provided with an armature *A* (Fig. 294), through which a

complete iron path for the lines of force is established, as shown in Fig. 295. The strength of such a magnet depends upon the quantity and quality and form of the iron, but chiefly upon the number of *ampere turns* which encircle it, the expression *ampere turns* denoting the product of the number of turns of wire about the magnet by the number of amperes flowing in each turn. Thus a current of $\frac{1}{100}$ ampere flowing 1000 times around a core will make an electromagnet of precisely the same strength as a current of 1 ampere flowing 10 times about the core. (See modern lifting magnet opposite page 335.)

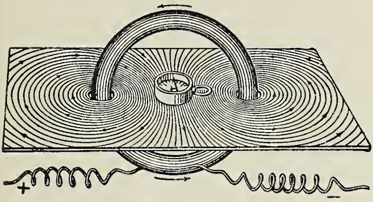


FIG. 296. Magnetic field about a circular coil carrying a current

The galvanometer. Electric currents are, in general, measured by the strength of the magnetic effect which they are able to produce under specific conditions. Thus, if the wire carrying a current is wound into circular form, as in Fig. 296, the right-hand rule shows us that the shape of the magnetic field at the center of the coil is similar to that shown in the figure. If, then, the coil is placed in a north-and-south plane and a compass needle is placed at the center, the passage of the current through the coil tends to deflect the needle so as to make it point east and west. The amount of deflection under these conditions is taken as the measure of current strength.

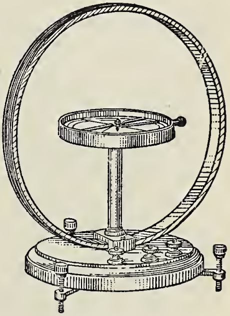


FIG. 297. A fixed-coil galvanometer

Nearly all current-measuring instruments consist essentially either of a small compass needle at the center of a fixed coil, as in Fig. 297, or of a movable coil suspended

between the poles of a fixed magnet in the manner illustrated roughly in Fig. 298. This type is known as the D'Arsonval galvanometer (see Fig. 299) in honor of its inventor. The passage of the current through the coil produces a deflection, in the first case, of the magnetic needle with reference to the fixed coil, and, in the second case, of the coil with reference to the fixed magnet. If the instrument has been calibrated to give the strength of the current directly in amperes, it is called an *ammeter*; otherwise, a *galvanometer*.

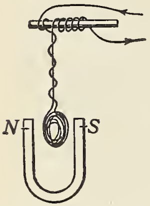


FIG. 298. Simple suspended-coil galvanometer

The commercial ammeter. Fig. 300 shows the construction of the usual form of commercial ammeter. The coil c is pivoted on jewel bearings and is held at its zero position by a spiral spring p. It loosely

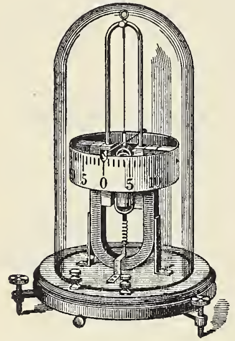


FIG. 299. A lecture-table galvanometer of the D'Arsonval type

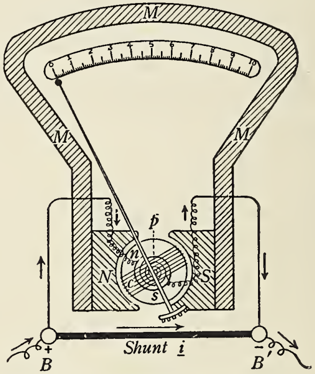
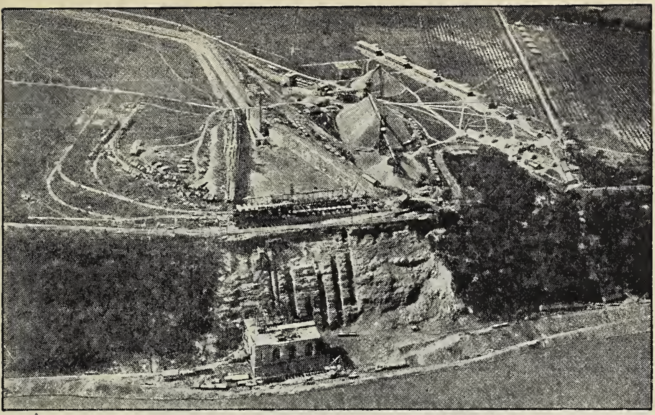
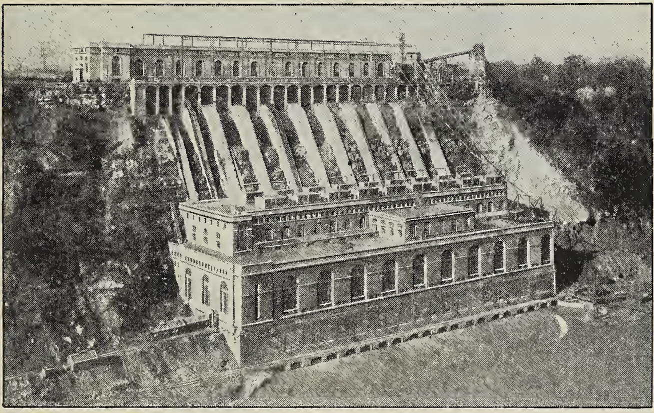


FIG. 300. Construction of a commercial ammeter

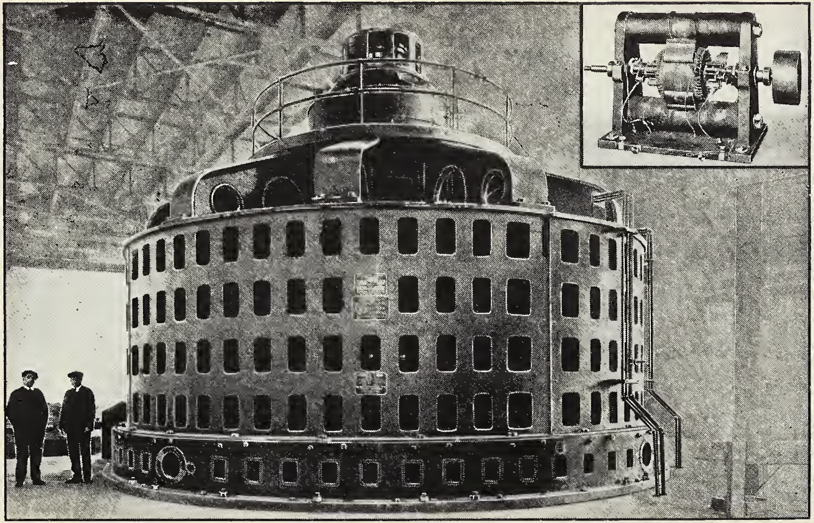
surrounds and freely turns about a cylindrical mass of soft iron. When a current flows through the instrument, if it were not for the spring p, the coil would turn through about 120°,





Magnificent Half-Million-Horsepower Hydroelectric Station at Queenston, Canada

The upper picture shows the station in construction with the $12\frac{3}{4}$-mile canal and partly blasted rock for penstocks. The lower picture shows the completed plant. Water drops 305 feet to turbines, which abstract its energy almost completely, as shown by the quietness of water from the tailrace. (Courtesy of the Hydroelectric Power Commission of Ontario, Canada)



Earliest and Latest Forms of Dynamos Built in the United States

The dynamo in the upper right-hand corner is the first built in the United States (a 3-kilowatt, 150-volt replica by Cornell students in 1875 of the original Gramme dynamo built in France in 1873). The other dynamo is one of three huge 65,000-kilowatt, 12,000-volt turbine-driven generators recently installed at Niagara Falls. The one machine is 26 inches high; the other, 26 feet. (Photograph used by courtesy of the General Electric Company)

or until its N pole came opposite the S pole of the magnet (Fig. 300). This zero position of the coil is chosen because it enables the scale divisions to be nearly equal. The conductor i, called a *shunt*, carries nearly all the current that enters the instrument at B, only an *exceedingly small* portion of it going through the moving coil c. The shunt is usually placed inside the instrument.

The electric bell. The electric bell (Fig. 301) is one of the simplest applications of the electromagnet. When the button P is pressed (Figs. 301 and 302), the electric circuit

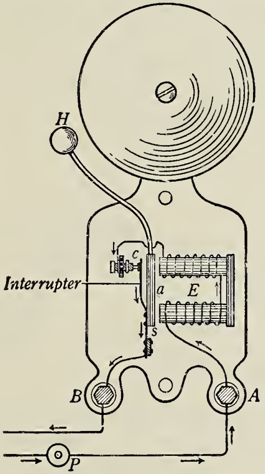


FIG. 301. The electric bell

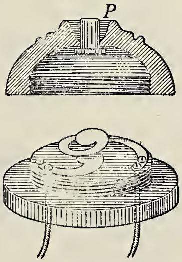


FIG. 302. Cross section of an electric push button

of the battery is closed, and a current flows in at A, through the coils of the magnet, over the closed contact c, and out again at B. But as soon as this current is established, the electromagnet E pulls over the armature a, and in so doing breaks the contact at c. This stops the current and demagnetizes the magnet E. The armature is then thrown back against c by the elasticity of the spring s which supports it. No sooner is the contact made at c than the current again begins to flow and the former operation is repeated. Thus the circuit is automatically made and broken at c, and the hammer H is in consequence set into rapid vibration against the rim of the bell.

The telegraph. The electric telegraph is another simple application of the electromagnet. The principle is illustrated by an early form shown in Fig. 303. As soon as the key *K*, at Chicago for example, is closed, the current flows over the line to, we will say, New York. There it passes through the electromagnet *m*, and thence back to Chicago through the earth. The armature *b* is held down by the electromagnet *m* as long as the key *K* is kept closed. As soon as the circuit is broken at *K* the armature is pulled up by the spring *d*. By means of a clockwork device the tape *c* is drawn along at a uniform rate beneath the pencil or pen carried by the armature *b*. A very short time of closing of *K* produces a dot upon

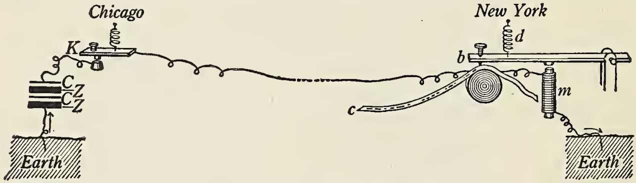


FIG. 303. Principle of the telegraph

the tape; a longer time, a dash. As the Morse, or telegraphic, alphabet consists of certain combinations of dots and dashes, any desired message may be sent from Chicago and recorded in New York. Later the message was not recorded on a tape, for operators learned to read messages by ear, a very short interval between two clicks being interpreted as a dot, a longer interval as a dash.

At the present time the dot-and-dash method of transmission has been largely replaced in commercial work by complicated sending and receiving machines. On the sending end a clerk types the message on a keyboard which is essentially the same as that used on a standard typewriter. The message is transformed automatically into electrical impulses, which on the receiving end are again translated into letters automatically typed on a narrow gummed tape. The operator pastes this strip on a regular telegraph blank.

❰The first commercial telegraph line was built by S.F.B. Morse (see opposite page 352) between Baltimore and Washington. It was opened on May 24, 1844, with the now famous message, "What hath God wrought!"

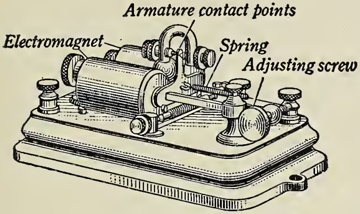


FIG. 304. The relay

❰**The relay and sounder.** Since the current that comes over a long telegraph line is of small amperage, it is necessary to make the armature of the electromagnet of the receiving instrument extremely light to respond to the action of the current. The electromagnet of this instrument is made of many thousand turns of fine wire, to secure the requisite number of ampere turns (p. 347) to work the armature. The clicks of such an armature are not sufficiently loud to be read easily by an operator. Hence at each station there is introduced a local circuit, which contains a local battery and a second and heavier electromagnet, which is called a sounder. The electromagnet on the main line is called the relay (Figs. 304 and 306). The sounder has a very heavy armature (Fig. 305, *A*), which is so arranged that it clicks both when it is drawn down by its electromagnet against the stop *S* and when it is pushed up again by its spring, on breaking the current, against the stop *t*. The interval which elapses between these two clicks indicates to the operator whether a dot or a dash is sent. The small current in the main line simply serves to close and open the circuit in the local battery which operates the sounder (Fig. 306). The electromagnets of the relay and the sounder differ in that the latter consists of a few hundred turns of coarse wire and carries a comparatively large current.

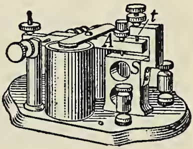


FIG. 305. The sounder

Plan of a telegraphic system. The actual arrangement of the various parts of a telegraphic system is shown in Fig. 306. When an operator at Chicago wishes to send a message to New York, he first opens the switch which is connected to his key, and which is always kept closed except when he is sending a message. He then begins to operate his key, thus controlling the clicks of both his own sounder and that at New York. When the Chicago switch is closed and the one at New York open, the New York operator is able to send a message back over the same line. In practice a message is not usually sent as far as from Chicago to New York over a single line, except in the case of trans-oceanic cables. Instead it is automatically transferred, say at Cleveland, to a second line, which carries it on to Buffalo, where it is again transferred to a third line, which carries it on to New York. The transfer is made in precisely the same way as the transfer from the main circuit to the sounder circuit. If, for example, the sounder circuit at Cleveland is lengthened so as to extend to Buffalo, and if the sounder itself is replaced by a relay (called in this case a repeater), and the local battery by a line battery, then the sounder circuit has been transformed into a repeater circuit, and all the conditions are met for an automatic transfer of the message at Cleveland.

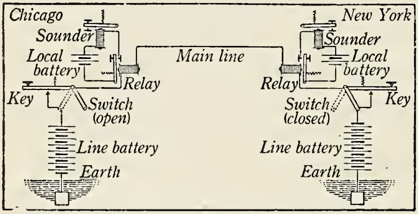
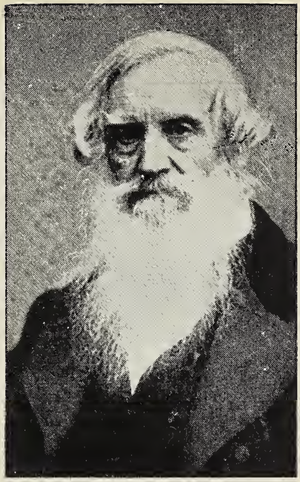


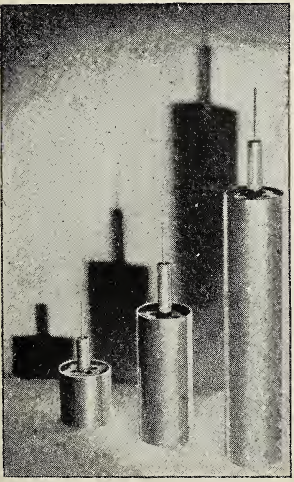
FIG. 306. Simple telegraphic system

Summary. Right-hand rules. **(1) Grasp a conductor with the right hand, the thumb pointing in the direction of the current; the fingers then point along the magnetic lines of force. (2) Grasp a helix with the right hand so that the fingers point in the direction of the current in the coils; the thumb then points in the direction of the magnetic lines, that is, toward the *N* pole.**

Ampere turns determine the strength of an electromagnet.

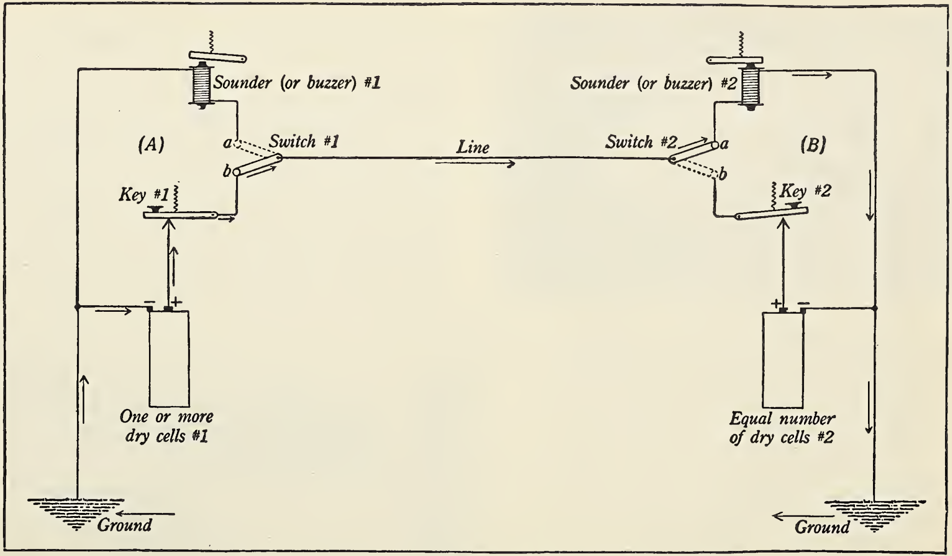
Samuel F. B. Morse (1791–1872), the inventor of the electromagnetic recording telegraph and of the dot-and-dash alphabet known by his name, was born at Charlestown, Massachusetts, graduated at Yale College in 1810, invented the commercial telegraph in 1832, and struggled for twelve years in great poverty to perfect it and secure its proper presentation to the public. The first public exhibition of the completed instrument was made in 1837 at New York University, signals being sent through 1700 feet of copper wire. It was with the aid of a $30,000 grant from Congress that the first commercial line was constructed in 1844 between Washington and Baltimore





Coaxial conductors. A hundred years after the first public exhibition of the Morse telegraph it is possible, with the aid of carrier currents sent over a new "million-cycle coaxial line" (see left) developed by the American Telephone and Telegraph Company, to transmit simultaneously, without mutual interference, 240 separate telephone conversations. The coaxial conductor consists of a $\frac{7}{8}$-inch lead cylinder surrounding a single small air-insulated wire. At the sending end conversations from 240 telephone lines are gathered together and placed on this single wire, and at the receiving end these 240 conversations are sorted out over as many different circuits. This same current transmits simultaneously both telegraph and telephone messages

A Century of Wire Communications



A Practical Circuit for a Telegraph Line between Homes

The latest transatlantic cables are wrapped with an alloy called "Permalloy," consisting of 80 per cent nickel and 20 per cent iron. It has thirty times the permeability of soft iron for low degrees of magnetization. This has increased the speed of cablegrams from five to eight times, thus very largely reducing the number of cables required

Currents are usually measured with galvanometers. These may have either (1) a movable coil with a stationary magnet or (2) a movable magnet with a stationary coil.

The multiple-stroke electric bell depends for its continued action upon an automatic circuit breaker.

The telegraph sends code messages through an electromagnet operated by making and breaking an electric circuit.

The Morse telegraph system is of the closed-circuit type, the current flowing constantly when the line is not in use.

A telegraph sounder has only a few turns in its helix, which must carry a relatively strong current to get the necessary ampere turns for operation.

The telegraph relay takes a weak current from the line through a helix of thousands of turns of wire, transmitting its impulses to a second circuit.

QUESTIONS AND PROBLEMS

A

1. In what direction will the north pole of a magnetic needle be deflected if it is held above a current flowing from north to south?

2. A man stands beneath a north-and-south trolley line and finds that a magnetic needle in his hand has its north pole deflected toward the east. What is the direction of the current flowing in the wire?

3. Why would an electromagnet made by winding bare wire on a bare iron core be worthless as a magnet?

4. (*a*) If one looks down on the ends of a U-shaped electromagnet, does the current encircle the two coils in the same or in opposite directions? (*b*) Does it run clockwise or counterclockwise about the *N* pole?

5. How could you test whether or not the strength of an electric current is the same in all parts of a circuit? Try it.

6. In a galvanometer consisting of a stationary coil and a magnetic compass, what force opposes the motion due to the magnetic field of the current?

7. What force acts to oppose the motion of the coil (*a*) in the suspended-coil galvanometer? (*b*) in the commercial ammeter represented in Fig. 300?

8. Draw a diagram showing how an electric bell works.

9. Draw a diagram of a short two-station telegraph line which has only one instrument at each station.

10. A certain relay has 8600 turns of wire in its helix and will operate on .02 ampere. How many ampere turns does this make?

11. (*a*) In the telegraph system shown in Fig. 306 does a current flow or not when the line is not in use? (*b*) Why is this necessary?

B

1. If the earth's magnetism is due to a surface charge rotating with the earth, must this charge be positive or negative in order to produce the sort of magnetic poles which the earth has? (This has been suggested as a cause of a part of the earth's magnetism.)

2. The plane of a suspended loop of wire is east and west. A current is sent through it, passing from east to west on the upper side. What will happen to the loop if it is perfectly free to turn?

3. Two electromagnets have identical cores. One is wound with 5000 turns of fine wire and carries .04 ampere; the other is wound with 100 turns of thicker wire. How many amperes must flow through the 100-turn helix to produce the same magnetic effect in the core?

4. In calibrating an ammeter the current which produces a certain deflection is found to deposit $\frac{1}{2}$ g of silver in 50 min. What is the strength of the current?

5. Examine the diagram opposite page 353 and answer the following questions: (*a*) With switches as shown, who does the telegraphing, (*A*) or (*B*)? (*b*) How must the switches be set for (*B*) to do the sending? Trace the current when (*B*) sends. (*c*) When an operator is through sending, how must both switches be left so that either (*A*) or (*B*) may call the other? (*d*) Why do the cells not run down, even though both switches are at *b* and both keys closed?

6. How does a compass needle arrange itself relative to the lines of force about a wire carrying a current?

7. In Fig. 300 why is a cylindrical mass of soft iron placed between the poles of the magnet?

8. How could a galvanometer (D'Arsonval) be converted into an ammeter?

9. What is the function of the shunt in the construction of the ammeter?

Resistance and Electromotive Force

Electrical resistance.* In the study of flowing liquids there are three fundamental quantities which have to do with the flow of water through a pipe: the rate of flow, the resistance which the pipe offers to the free flow, and the pressure in the liquid producing the flow. We might expect to deal with three similar quantities in considering the flow of electrical charges through a wire. We have already discussed rate of flow, or current, and its measurement. Let us investigate experimentally the resistance offered by a wire to the flow of charges.

Connect the circuit of a galvanic cell through a lecture-table ammeter or any low-resistance galvanometer and, for example, 20 ft of No. 30 copper wire, and note the deflection of the needle. Then replace the copper wire by an equal length of No. 30 German-silver wire. The deflection will be found to be a very small fraction of what it was at first.

Therefore a cell which is capable of developing a certain fixed electrical pressure is able to force very much more current through a given wire of copper than through an exactly similar wire of German silver. We say, therefore, that German silver offers a higher *resistance* to the passage of electricity than does copper. Similarly every particular substance has its own characteristic power of transmitting electric currents. Since silver is the best conductor known, resistances of different substances are commonly referred to it as a standard, and the ratio between the resistance of a given wire of any substance and the resistance of an exactly similar silver wire is called the *specific resistance* of that substance. The specific resistances of some of the commoner metals in terms of silver are given below:

Silver	1.00	Soft iron	6.00	German silver . .	20.3
Copper	1.06	Platinum	6.14	Mercury	58.7
Aluminum . . .	1.74	Hard steel . . .	13.5	Nichrome . . .	61.3

* This subject should be accompanied and followed by laboratory experiments on Ohm's law, on the comparison of wire resistances, and on the measurement of internal resistances. See, for example, Experiments 40, 41, 42, and 46 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

We find that as we increase the length of a conductor, we increase its resistance in proportion. We find also that if we increase its area of cross section, keeping the length the same, we decrease its resistance. This leads us to the law of resistance:

The resistance of any conductor is (1) directly proportional to its length, and (2) inversely proportional to the area of its cross section or to the square of its diameter.

The unit of resistance is the *ohm*, named after the German physicist Georg Simon Ohm (1787–1854). A length of 9.71 feet of No. 30 copper wire or 6.1 inches of No. 30 German-silver wire has a resistance of about 1 ohm. *The legal definition of the ohm is a resistance equal to that of a column of mercury 106.3 centimeters long and 1 square millimeter in cross section, at 0° C.*

The resistance type of theater dimmer illustrates one of the more important means of controlling and altering the strength of electric currents, namely, the introduction into the circuit of a variable resistance.

Resistance and temperature. Close the circuit of a galvanic cell through a galvanometer of very low resistance and about 10 ft of No. 30 iron wire wrapped around a strip of asbestos. Observe the deflection of the galvanometer as the wire is heated in a Bunsen flame. As the temperature rises higher and higher, the current will be found to fall continually.

The experiment shows that *the resistance of iron increases with rising temperature.* This is a general law which holds for all metals. In the case of liquid conductors, on the other hand, the resistance usually decreases with increasing temperature. Carbon and a few other solids show a similar behavior; the filament in the early form of carbon incandescent electric lamp has when burning at full candle power only about half the resistance that it has when cold.

Electromotive force and its measurement.* The potential difference which a galvanic cell or any other generator

* This subject should be preceded or accompanied by laboratory work on E.M.F. See, for example, Experiment 39 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

of electricity is able to maintain between its terminals when these terminals are not connected by a wire — that is, the total electrical pressure which the generator is capable of exerting — is commonly called its *electromotive force*, usually abbreviated to E.M.F. This P.D. might be measured, as on page 327, by the deflection produced in an electroscope when one terminal is connected to the case of the electroscope and the other terminal to the knob. Potential differences are in fact measured in this way in all so-called electrostatic voltmeters.

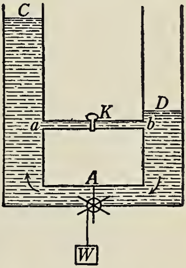


FIG. 307. Hydrostatic analogy of the action of a galvanic cell

The more common type of potential-difference measurer consists, however, of an instrument made like a galvanometer (Fig. 299), except that within the instrument a high resistance is placed in series with the movable coil. The amount of electric current which goes through the instrument is proportional to the difference in electrical pressure existing between its terminals when these are touched to the two points whose P.D. is sought. The principle underlying this type of voltmeter will be better understood from a consideration of the following water analogy. If the stopcock *K* (Fig. 307) in the pipe connecting the water tanks *C* and *D* is closed, and if the water wheel *A* is set in motion by applying a weight *W*, the wheel will turn until it creates such a difference in the water levels between *C* and *D* that the back pressure against the left face of the wheel stops it and brings the weight *W* to rest. In precisely the same way the chemical action within the galvanic cell whose terminals are not joined (Fig. 308) develops positive and negative charges upon these terminals; that is, creates a P.D. between them until the back electrical pressure through the cell due to this P.D. is sufficient to put a stop to further chemical action. The seat of the E.M.F. is at the surfaces of contact of the metals with the acid, where the chemical actions take place.

Now if the water reservoirs (Fig. 307) are put in communication by opening the stopcock K, the difference in level between C and D will begin to fall, and the wheel will begin to build it up again. But if the carrying capacity of the pipe ab is small in comparison with the capacity of the wheel to remove water from D and supply it to C, then the difference of level which permanently exists between C and D when K is open will not be appreciably smaller than when it is closed. In this case the current which flows through ab may obviously be taken as a measure of the difference in pressure which the pump is able to maintain between C and D when K is closed.

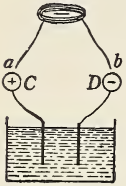


FIG. 308. Measurement of P.D. between the terminals of a galvanic cell

In precisely the same way, if the terminals C and D of the cell (Fig. 308) are connected by attaching to them the terminals a and b of any conductor, they at once begin to discharge through this conductor, and their P.D. therefore begins to fall. But if the chemical action in the cell is able to recharge C and D very rapidly in comparison with the ability of the wire to discharge them, then the P.D. between C and D will not be appreciably lowered by the presence of the connecting conductor. In this case the current which flows through the conducting coil, and therefore the deflection of the needle at its center, may be taken as a measure of the electrical pressure developed by the cell, that is, of the P.D. between its unconnected terminals.

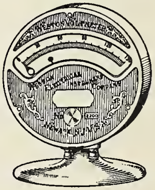


FIG. 309. Lecture-table voltmeter

The common voltmeter (Fig. 309) is, then, exactly like an ammeter, except that it offers so high a resistance to the passage of electricity through it that it does not appreciably reduce the P.D. between the points to which it is connected.

The commercial voltmeter. In Fig. 310 is shown the principle of construction of the common form of commercial voltmeter.

It differs from the ammeter (Fig. 300) in that the shunt is omitted, and a high-resistance coil R is put in series with the moving coil c. The resistance of a voltmeter may be many thousand ohms. The current that passes through it is very small.

The electromotive forces of galvanic cells. When constructing a galvanic cell, we should like to know on what factors its E.M.F. depends. We perform an experiment as follows to find out:

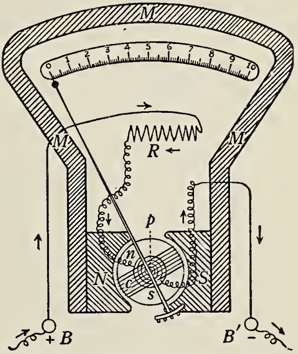


FIG. 310. Principle of commercial voltmeter

Connect a voltmeter of any sort to the terminals of a simple galvanic cell, like that of Fig. 275. Then change through wide limits the distance between the plates and the degree to which they are covered by the solution. It will be found that the deflection produced is altogether independent of the shape or size of the plates or their distance apart. But if the nature of the plates is changed, the deflection changes. Thus copper and zinc in dilute sulfuric acid have an E.M.F. of 1 volt, carbon and zinc show an E.M.F. of at least 1.5 volts, and carbon and copper show an E.M.F. of very much less than a volt. Similarly, by changing the nature of the liquid in which the plates are immersed we can produce changes in the deflection of the voltmeter.*

We learn, therefore, that *the E.M.F. of a galvanic cell depends simply upon the materials of which the cell is composed, and not at all upon the shape, size, or distance apart of the plates.*

Fall of potential along a conductor carrying a current. A P.D. exists not only between the terminals of a cell on open circuit but also between any two points on a conductor through

* A vertical lecture-table voltmeter (Fig. 309) and a similar ammeter are desirable for this and some of the following experiments, but homemade high-resistance and low-resistance galvanometers, like those described in *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis, are thoroughly satisfactory, except for the fact that one student must take the readings for the class.

which a current is passing. For example, in the electric circuit shown in Fig. 311 the potential at the point *a* is higher than that at *m*, that at *m* higher than that at *n*, etc. just as, in the water circuit shown in Fig. 312, the hydrostatic pressure at *a* is greater than that at *m*, that at *m* greater than that at *n*, etc. The fall in the water pressure between *m* and *n* (Fig. 312) is measured by the waterhead *n's*. If we wish to measure the fall in electrical potential between *m* and *n* (Fig. 311), we

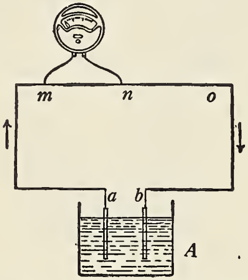


FIG. 311. Showing method of connecting voltmeter to find P.D. between any two points *m* and *n* on an electric circuit

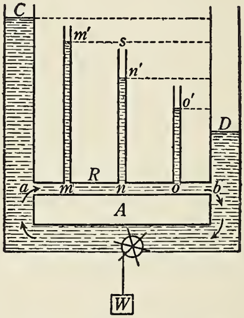


FIG. 312. Hydrostatic analogy of fall of potential in an electric circuit

touch the terminals of a voltmeter to these points in the manner shown in the figure. Its reading gives us at once the P.D. between *m* and *n* in volts, provided always that its own current-carrying capacity is so small that it does not appreciably lower the P.D. between the points *m* and *n* by being touched across them; that is, provided the current which flows through it is negligible in comparison with that which flows through the conductor which already joins the points *m* and *n*.

Summary. **There are three fundamental quantities having to do with the flow of current through a wire: current, resistance, and P.D. The practical units of measurement of these quantities are the ampere, the ohm, and the volt, respectively.**

The resistance of a conductor varies directly with its length and inversely with its cross-sectional area or the square of its diameter.

$$\frac{r'}{r''} = \frac{l'}{l''}; \; \frac{r'}{r''} = \frac{s''}{s'} = \frac{d''^2}{d'^2}.$$

The E.M.F. of any generator is the total electrical pressure it can develop on open circuit.

A magnetic voltmeter is a high-resistance galvanometer calibrated to give a direct reading in volts.

Voltmeters are attached directly across the terminals of a generator to measure its E.M.F., but are used as a shunt to measure fall in potential (P.D.) in any part of a circuit.

QUESTIONS AND PROBLEMS

A

1. If 300 ft of No. 18 copper wire has a resistance of 2 ohms, what is the resistance of 800 ft of it?

2. The resistance of a certain piece of German-silver wire is 1 ohm. What will be the resistance of another piece of the same length but of twice the diameter?

3. How does the resistance of a tungsten lamp when not lighted compare with its resistance when giving light?

4. If the potential difference between the terminals of a cell on open circuit is to be measured by means of a galvanometer, why must the galvanometer have a high resistance? (See page 358.)

B

1. Consider the diameter of No. 20 wire to be three times that of No. 30. A certain No. 30 wire 1 m long has a resistance of 6 ohms. What would be the resistance of 4 m of No. 20 wire made of the same metal?

2. How long a piece of No. 30 copper wire has the same resistance as a meter of No. 30 German-silver wire? (See table of specific resistances, p. 355.)

3. Upon what four factors does electrical resistance depend?

4. How does the resistance of a carbon lamp when not lighted compare with its resistance when giving light?

5. Why are the solutions used in electroplating usually kept at a high temperature?

6. Why are the filaments in tungsten lamps made so threadlike?

Ohm's Law

Ohm's law. We have seen that the measurement of electric current involves three quantities similar to those used in the measurement of liquid flow. We should expect the relations between these quantities to be similar. For the case of liquids the rate of flow through any given pipe is proportional to the head, or difference in liquid pressure between the ends of the pipe. Also, for a given head, the rate of flow is inversely proportional to the resistance of the pipe. The corresponding relation for electrical quantities, first discovered and stated by Ohm in 1826, is *The current in a circuit is always directly proportional to the E.M.F. existing in the circuit and inversely proportional to the total resistance in the circuit.* In other words, current equals E.M.F. divided by resistance. Algebraically, if we use the usual notation, letting I represent the current in amperes, E the E.M.F. in volts, and R the resistance in ohms, Ohm's law as applied to a complete circuit is

$$I = \frac{E}{R}; \text{ that is, current} = \frac{\text{electromotive force}}{\text{resistance}}. \tag{1}$$

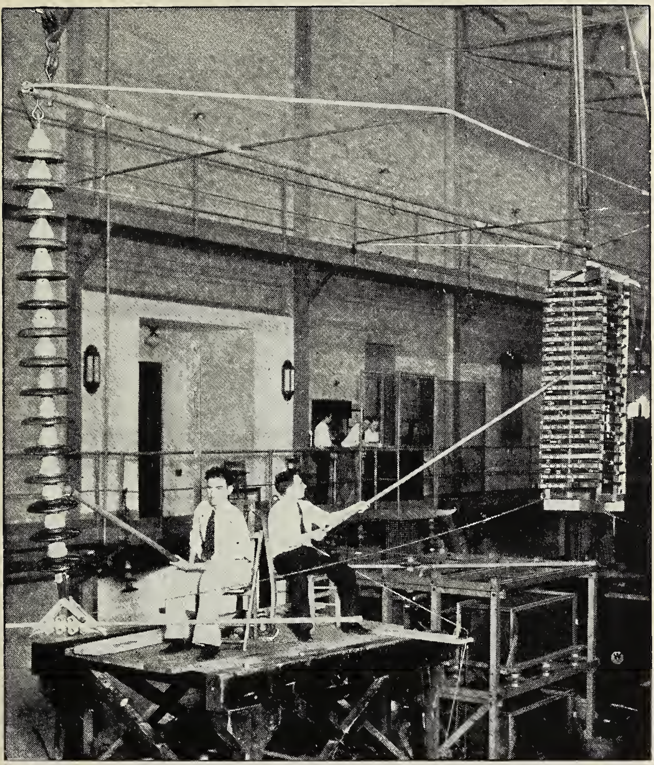
As applied to any portion of an electric circuit, Ohm's law is

$$I = \frac{\text{P.D.}}{R}; \text{ that is, current} = \frac{\text{potential difference}}{\text{resistance}}, \tag{2}$$

where P.D. represents the difference of potential in volts between any two points in the circuit, and R the resistance in ohms of the conductor connecting these two points. This is one of the most important laws in physics.

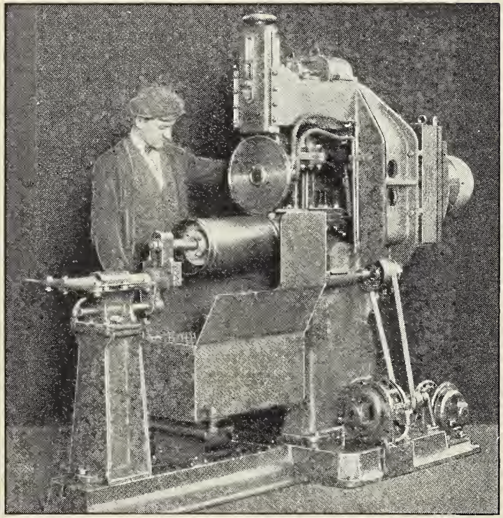
Both of the above statements of Ohm's law are included in the equation

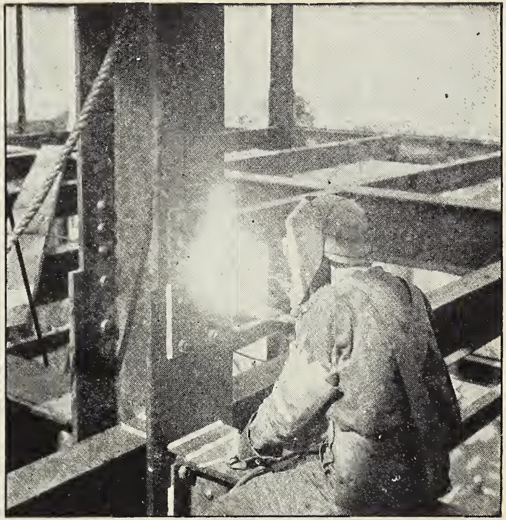
$$\text{Amperes} = \frac{\text{volts}}{\text{ohms}}. \tag{3}$$



Testing a String of Insulators in a Million-Volt Laboratory

To find whether the total potential is distributed uniformly along the string the left-hand student touches a particular point on the string with a small wire attached to his long insulating pole. His companion then finds the point on the water resistance — garden hose filled with water — to which he can bring the other end of the same wire without observing any spark on contact. The potentials at the line ends of the wire are then the same. The P. D. along the water resistance is constant, so that the potential distribution along the string is at once obtained





Electric Welders

At the left is a resistance welding machine. Hundreds of amperes of current pass through the small point of contact of the rotary wheel with the seam to be welded, thus generating the requisite heat. At the right is shown an arc welder making column-to-beam joints on a frame of a new building. (Courtesy of the General Electric Company)

If the E.M.F. is unknown, the law takes the form $E = IR$. If the resistance is unknown, the form is $R = E/I$.

Example: A heater has a voltage of 110 volts between its terminals and a resistance of 10 ohms when hot. What current will it carry?

Solution: $I = \frac{E}{R} = \frac{110}{10} = 11$ amperes.

Internal resistance of a galvanic cell. Connect the zinc and copper plates of a simple galvanic cell to an ammeter and increase the distance between the plates. The deflection of the needle will be found to decrease, or if the amount of immersion is decreased, the current also will decrease.

Now, since the E.M.F. of a cell was shown on page 359 to be wholly independent of the area of the plates immersed or of the distance between them, the E.M.F. in this case must have remained the same throughout all the changes in the cell. But if the current changes while the E.M.F. stays the same, Ohm's law tells us that the total resistance in the circuit must change. Since the wire which constitutes the outside portion of the circuit has remained the same, we must conclude that *the liquid within the cell, as well as the external wire, offers resistance to the passage of the current.* The difference between the open-circuit E.M.F. of a cell and the P.D. across its terminals is the potential required to send that current through the internal resistance of the cell. This internal resistance of the liquid is directly proportional to the distance between the plates, and inversely proportional to the area of the immersed portion of the plates. If, then, we represent the external resistance of the circuit of a galvanic cell by R_e and the internal by R_i, Ohm's law as applied to the entire circuit takes the form

$$I = \frac{E}{R_e + R_i}. \qquad (4)$$

Thus, if a simple cell has an internal resistance of 2 ohms and an E.M.F. of 1 volt, the current which will flow through the circuit when its terminals are connected by 9.71 feet of No. 30 copper wire (1 ohm) is $\frac{1}{1+2} = .33$ ampere.

Measurement of any resistance by ammeter-voltmeter method. The simplest way of measuring the resistance of a wire, or, in general, of any conductor, is to connect it into the circuit of a galvanic cell in the manner shown in Fig. 313. The ammeter A is inserted to measure the current, and the voltmeter V to measure the P.D. between the ends a and b of the wire r, the resistance of which is sought. The resistance of r in ohms is obtained at once from the ammeter and voltmeter readings with the aid of the law $I = \text{P.D.}/R$, from which it follows that $R = \text{P.D.}/I$. Thus, if the voltmeter indicates a P.D. of 0.4 volt and the ammeter a current of 0.5 ampere, the resistance of r is $0.4/0.5 = .8$ ohm.*

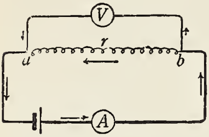


FIG. 313. Measurement of resistance by ammeter-voltmeter method

Resistance by calculation. With the aid of the table given below, it is possible to compute the resistance of any wire when its material, diameter, and length are known. A mil-foot of wire is a wire 1 foot long and having a diameter of 1 mil (one thousandth of an inch). Its area is said to be 1 circular mil. A wire two thousandths of an inch in diameter would have a diameter of 2 mils, and its area in circular mils would be 4. Thus, to find the area of a wire in circular mils, first express its diameter in mils, and then square this number. The resistance of any wire may then be calculated by the use of the following formula:

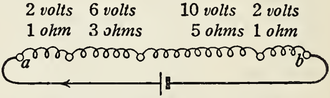


FIG. 314. Series connections

$$R = \frac{kl}{d^2},$$

where k is the resistance of a mil-foot of wire as given in the table below, l its length in feet, and d^2 its cross-sectional area *in circular mils*.

* For Wheatstone's-bridge method see Experiment 41 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

The following table gives the resistance in ohms per mil-foot for wires of various materials:

Silver	9.82	Platinum	60.3
Copper	10.4	Iron	60.3
Aluminum	17.05	German silver (18 per cent)	199
Tungsten	33.2	Nichrome	602

Series connections. Conductors may be connected either in *series*, so that all the current goes through first one and then the next, as in Fig. 314, or in *parallel*, so that the current divides, part of it going through one conductor and part through another, as in Fig. 315. A little consideration will make evident the following three laws of series circuits:

1. *The current is the same in every part of a series circuit.*
2. *The total resistance of a series circuit is the sum of the resistances of its parts.*
3. *The total voltage across a series circuit is the sum of the voltages across the parts.*

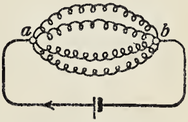


FIG. 315. Parallel connections

Thus in Fig. 314 the total resistance between a and b is 10 ohms, the total P.D. is 20 volts, and the current throughout by Ohm's law is 2 amperes.

Parallel connections. It is clear that, since in a parallel circuit the current divides, part going through one branch, part through another, the total current in the circuit may be found by adding the currents in all the branches. It is also clear that the difference in potential between the two junction points must be the same through one branch as through another. As to resistance, if we increase the number of wires in parallel between two points, we furnish paths over which more current may flow and thus reduce the total resistance. Adding more parallel branches may be thought of as increasing the area of cross section of a single resistance wire. This, as we have learned, reduces the resistance.

The opposite of resistance — that is, the amount of current that a wire will carry at a given P.D. — is called *conductance*, and is equal to the reciprocal of resistance. To find

the conductance (and from it the resistance) of a parallel circuit we add together the conductances of the branches. Thus, if there are four branches in parallel with resistances r_1, r_2, r_3, r_4, the total conductance $\frac{1}{r}$ is given by

$$\frac{1}{r} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \frac{1}{r_4}.$$

The three laws of parallel circuits are, then,

1. *The total current in a parallel circuit is the sum of the currents in the branches.*

2. *The P.D. across a parallel circuit is the same across each of the branches.*

3. *The conductance of a parallel circuit is the sum of the conductances of the branches.*

Shunts. A wire connected in parallel with another wire is said to be a *shunt* to that wire. Thus the conductor X (Fig. 316) is said to be shunted across the resistance R. Under such conditions the currents carried by R and X will be inversely proportional to their resistances, so that if X is 1 ohm and R is 10 ohms, R will carry $\frac{1}{10}$ as much current as X, or $\frac{1}{11}$ of the whole current. In other words, since the carrying power, or *conductance*, of X is ten times that of R, ten times as much current will flow through X as through R, or $\frac{10}{11}$ of the whole current will pass through the shunt. The ammeter (Fig. 300) uses a shunt of exceedingly small resistance.

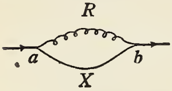


FIG. 316. A shunt

Summary. Ohm's law. Amperes $= \frac{\text{volts}}{\text{ohms}}$.

The resistance of any number of conductors in series is the sum of their individual resistances.

The resistance of a group of similar conductors in parallel is equal to the resistance of one of them divided by their number.

In a divided circuit consisting of two branches the strengths of the currents in the branches are inversely proportional to the resistances of the branches.

QUESTIONS AND PROBLEMS

A

1. How can you prove that the internal resistance of a cell becomes smaller (*a*) when the plates are made larger? (*b*) when they are placed closer together?

2. How much current will flow between two points whose P.D. is 2 volts, if they are connected by a wire having a resistance of 12 ohms?

3. If a voltmeter attached across the terminals of an incandescent lamp shows a P.D. of 110 volts and an ammeter connected in series with the lamp indicates a current of .5 ampere, what is the resistance of the incandescent filament? Make a diagram to explain the method.

4. Three wires, each having a resistance of 15 ohms, were joined in parallel and a current of 3 amperes was sent through them. How much was the P.D. of the ends of the wires?

5. Eleven lamps are connected in series with a generator which furnishes a P.D. of 550 volts. What is the voltage drop through each lamp?

6. Eleven lamps are connected in parallel with a generator furnishing 110 volts. What is the voltage drop across each lamp?

7. A voltmeter which has a resistance of 2000 ohms is shunted across the terminals A and B of a wire which has a resistance of 1 ohm. What fraction of the total current flowing from A to B will be carried by the voltmeter?

8. How would you arrange three 10-ohm coils so as to have a combined resistance of 15 ohms?

9. Find the resistance of (*a*) 1000 ft of copper wire having a diameter of .025 in.; (*b*) 1000 ft of German-silver wire of the same diameter.

B

1. An electric heater has 12 wires of equal resistance connected in parallel. The resistance of each wire when hot is 50 ohms. If the heater is operated on a 110-volt circuit, what will be the total current passing through the heater?

2. What length of No. 22 nichrome wire (diameter .025 in.) would be used to construct the heating element in a toaster drawing 5 amperes on a 110-volt house circuit?

3. A certain storage cell having an E.M.F. of 2 volts is found to furnish a current of 20 amperes through an ammeter whose resistance is .05 ohm. Find the internal resistance of the cell.

4. From a consideration of the formula $I = E/R$ state (*a*) in what two ways you may strengthen a current; (*b*) in what two ways you may weaken it.

5. The E.M.F. of a certain battery is 10 volts and the strength of the current obtained through an external resistance of 4 ohms is 1.25 amperes. What is the internal resistance of the battery?

6. Can you prove from a consideration of Ohm's law that when wires of different resistances are inserted in series in a circuit the P.D.'s between the ends of the various wires are proportional to the resistances of these wires?

7. Why is it desirable that an ammeter, which is used in the circuit in series for measuring currents, have as low a resistance as possible?

8. Draw a diagram showing how a 3-ohm coil, a 6-ohm coil, and a 10-ohm coil may be connected to give a total resistance of 12 ohms.

9. Why are the plates of a storage battery made large and placed close together?

10. How does the P.D. across the terminals of a small dry cell, such as we use in flashlights, compare with that of the standard dry cell?

11. If the conductor R in Fig. 316 has a resistance of 10 ohms and X has a resistance of 15 ohms, what fraction of the current flowing in the main circuit will go through each branch?

12. Why are Christmas-tree lights so often connected in series of eight lamps in each string?

13. What is the disadvantage of this arrangement?

Primary Cells

Study of the action of a simple cell. If the simple cell already described (that is, zinc and copper strips in dilute sulfuric acid) is carefully observed, it will be seen that, so long as the plates are not connected by a conductor, fine bubbles of gas are slowly formed at the zinc plate, but none at the copper

plate. As soon as the two strips are put into metallic connection, however, bubbles appear in great numbers about the copper plate (Fig. 317), and at the same time a current flows in the connecting wire. These are bubbles of hydrogen. They hinder the most efficient action of the cell. Their appearance on the zinc plate may be prevented by using a plate of chemically pure zinc or by *amalgamating* impure zinc, that is, coating it over with a thin film of mercury. But the bubbles on the copper cannot be thus disposed of. They are an invariable accompaniment of the current in the circuit. If the current is allowed to run for a considerable time, it will be found that the zinc wastes away, even though it has been amalgamated, but that the copper plate does not undergo any change.

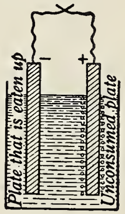


Fig. 317. Chemical actions in the voltaic cell

We learn, therefore, that the electric current in the simple cell is accompanied by the eating up of the zinc plate by the liquid, and by the appearance of hydrogen bubbles at the copper plate. In every type of galvanic cell, actions similar to these two are always found; that is, *one of the plates is always eaten up, and upon the other plate some element is deposited.* The zinc, which is eaten, is the one which we found to be negatively charged when tested (p. 336); hence, when the terminals are connected through a wire, the negative electrons flow through this wire from the zinc plate to the copper plate. This means, in accordance with the convention mentioned in the footnote on page 326, that *the direction of the current through the external circuit is always from the uneaten to the eaten plate.*

[**Local action and amalgamation.** The cause of the appearance of the hydrogen bubbles at the surface of impure zinc when dipped in dilute sulfuric acid is that little electric circuits are set up between the zinc and the small impurities in it (carbon or iron particles) in the manner indicated in Fig. 318. If the zinc is pure, these little local currents cannot be

set up, and consequently no hydrogen bubbles appear. Amalgamation stops this so-called *local action*, because the mercury dissolves the zinc, whereas it does not dissolve the carbon, iron, or other impurities. The zinc-mercury amalgam formed is a uniform, or homogeneous, substance which spreads over the whole surface and covers up the impurities. It is important, therefore, to amalgamate the zinc in a battery, in order to prevent the zinc from being eaten up when the cell is on open circuit. The zinc is under all circumstances eaten up when the current is flowing, amalgamation serving only to prevent its consumption when the circuit is open.

FIG. 318. Local action

Theory of the action of a simple cell. A simple cell may be made of any two unlike conductors immersed in a solution of almost any acid or salt. For simplicity let us examine the action of a cell composed of plates of zinc and copper immersed in a dilute solution of hydrochloric acid. The chemical formula for hydrochloric acid is HCl. This means that each molecule of the acid consists of one atom of hydrogen combined with one atom of chlorine. As was explained under electrolysis (p. 338), the acid, when dissolved in water, dissociates into positively and negatively charged ions (Fig. 319).

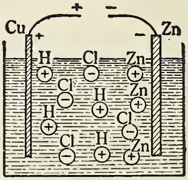


FIG. 319. Showing the dissociation of hydrochloric-acid molecules in water

When a zinc plate is placed in such a solution, the acid attacks it and pulls zinc atoms into solution. Now, whenever a metal dissolves in an acid, its atoms, for some unknown reason, go into solution bearing little positive charges. *The corresponding negative charges must be left on the zinc plate* in precisely the same way in which a negative charge is left on silk when positive electrification is produced on a glass rod by rubbing it with the silk. It is in this way, then, that we account for the negative charge which we found upon the zinc plate in the experiment described on page 336.

[The passage of positively charged zinc ions into solution gives a positive charge to the solution about the zinc plate; hence the hydrogen ions tend to be repelled away from this plate. When these repelled hydrogen ions reach the copper plate, some of them give up their charges to it and then collect as bubbles of hydrogen gas. It is in this way that we account for the positive charge which we found on the copper plate in the experiment on page 336.

[If the zinc and copper plates are not connected by an outside conductor, this passage of positively charged zinc ions into solution continues but a very short time, for the zinc plate soon becomes so strongly charged negatively that it pulls back on the + zinc ions with as much force as that with which the acid is pulling them into solution. In the same way the copper plate soon ceases to take up any more positive electricity from the hydrogen ions, since it soon gets a large enough + charge to repel them from itself with a force equal to that with which they are being driven out of solution by the positively charged zinc ions. It is in this way that we account for the fact that on open circuit no chemical action goes on in the simple galvanic cell, the zinc and copper plates simply becoming charged to a definite difference of potential which is called the E.M.F. of the cell.

[When, however, the copper and zinc plates are connected by a wire, a current at once flows from the copper to the zinc, and the plates thus begin to lose their charges. This allows the acid to pull more zinc into solution at the zinc plate, and allows more hydrogen to go out of solution at the copper plate. These processes, therefore, go on continuously so long as the plates are connected. Hence a continuous current flows through the connecting wire until the zinc is all eaten up or the hydrogen ions have all been driven out of the solution, that is, until either the plate or the acid has become exhausted.

Polarization. If the simple galvanic cell described is connected to a lecture-table ammeter through 2 or 3 feet of No. 30 German-silver wire, the deflection of the needle will

decrease slowly; but if the hydrogen is removed from the copper plate (this can be done completely only by removing and thoroughly drying the plate), the deflection will be found to return to its first value.

The experiment shows clearly that the observed falling off in current was due to the collection of hydrogen about the copper plate. This phenomenon of the weakening of the current from a galvanic cell is called the *polarization* of the cell. Some types of cells show it to a high degree.

Causes of polarization. The presence of the hydrogen bubbles on the positive, or copper, plate makes the current strength less for two reasons: first, since hydrogen is a nonconductor, by collecting on the plate it diminishes the effective area of the plate and therefore increases the internal resistance of the cell; secondly, the collection of the hydrogen about the copper plate lowers the E.M.F. of the cell, because it virtually substitutes a hydrogen plate for the copper plate, and we have already seen (p. 359) that a change in any of the materials of which a cell is composed changes its E.M.F. That there is a real fall in E.M.F. as well as a rise in internal resistance when a cell polarizes may be directly proved in the following way:

Heat a strip of bright, clean sheet copper in the tip of a Bunsen flame until it becomes black with a film of oxide of copper. Let it cool. (If the copper strip is plunged into water to cool it, the film of oxide will be largely detached.) Place it in dilute acid with a zinc plate to make a simple cell, and connect this to a lecture-table galvanometer of medium resistance. The current will remain strong as long as the hydrogen on reaching the copper plate can find oxygen with which to unite. When the supply of oxygen is exhausted, hydrogen bubbles will begin to appear on the copper plate and at the same time the current will weaken rapidly.

The various forms of galvanic cells in common use differ chiefly in the devices employed either for disposing of the hydrogen bubbles or for preventing their formation. The most common types of such cells are described in the following sections.

The Daniell cell. The Daniell cell consists of a zinc plate immersed in zinc sulfate and a copper plate immersed in copper sulfate, the two liquids being kept apart either by means of an unglazed earthen cup or else by gravity.

FIG. 320. The Weston normal cell

Copper ions are thus deposited on the positive plate instead of hydrogen, and hence the cell is one of very constant E.M.F., 1.08 volts. It is used on continuously closed circuit where constant currents are required.

The Weston normal cell; the volt. This cell consists of a positive electrode of mercury in a paste of mercurous sulfate, and a negative electrode of cadmium amalgam in a saturated solution of cadmium sulfate (Fig. 320). It is so easily and exactly reproducible and has an E.M.F. of such extraordinary constancy that it has been taken by international agreement as the standard in terms of which all E.M.F.'s and P.D.'s are rated.

Thus the *E.M.F. of a Weston normal cell at 20° C. is taken as 1.0183 volts. The legal definition of the volt is then "an electrical pressure equal to* $\frac{1}{1.0183}$ *of that produced by a Weston normal cell."*

FIG. 321. The dry cell

The dry cell. The dry cell (Fig. 321) is not really *dry*, since the mixture within is a moist paste. It contains approximately 100 grams of water. The zinc plate is in the form of a cylindrical can and holds the moist black mixture in which the carbon plate is embedded. This mixture consists of ammonium chloride, black oxide of manganese, zinc chloride, powdered petroleum coke, and a small amount of graphite. It is the action of the ammonium chloride upon the zinc that produces the current. The manganese dioxide overcomes the polarization due to hydrogen. The function

of the $ZnCl_2$ is to overcome the polarization due to ammonia. The immense advantage of this type of cell lies in the fact that the zinc is not at all eaten by the ammonium chloride when the circuit is open, and that therefore, unlike the Daniell cell, it can be left for an indefinite time on open circuit without deterioration. Its chief disadvantage, on the other hand, is the slowness of the chemical action of the manganese dioxide. Because of this slow action the cell is not suitable for use where a large continuous current is desired. It is used generally for momentary currents, as in doorbell circuits. It may be used for longer periods if the current required is small.

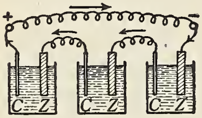


FIG. 322. Cells connected in series

The graphite diminishes internal resistance, which, in a fresh cell of ordinary size, may be less than $\frac{1}{20}$ of an ohm. Because of the low internal resistance these cells will deliver 30 or more amperes on momentary short circuit, and on account of their great convenience they are manufactured by the million annually. The voltage is 1.5.

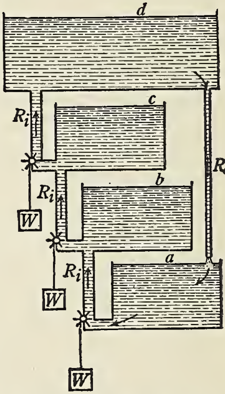
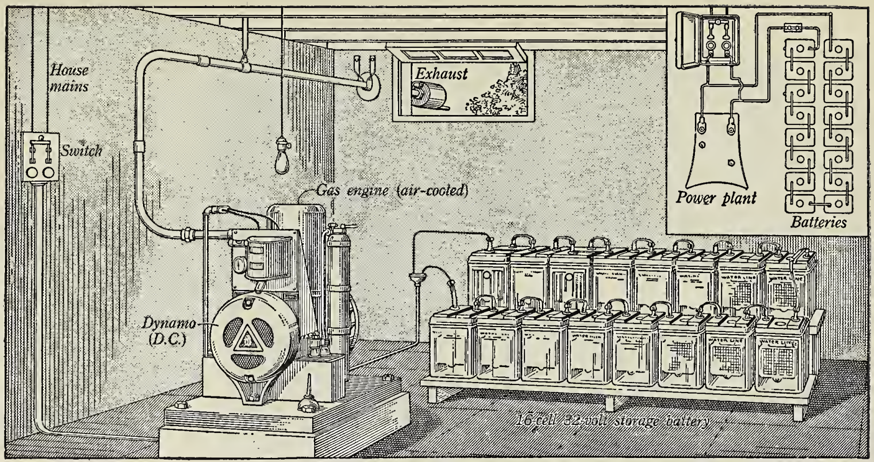


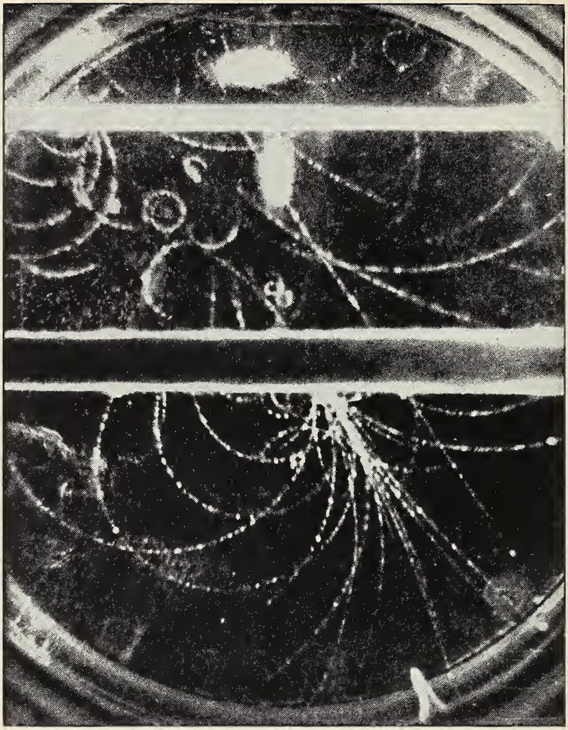
FIG. 323. Water analogy of cells in series

Combinations of cells. Cells, as well as external resistances, may be arranged either in series or in parallel. When they are connected in series, the zinc of one cell is joined to the copper of the second, the zinc of the second to the copper of the third, etc., the copper of the first and the zinc of the last being joined to the ends of the external resistance (Fig. 322). The E.M.F. of such a combination is the sum of the E.M.F.'s of the single cells. The internal resistance of the combination is also the sum of the internal resistances of the single cells. Hence, if the external resistances are very small, the current



A Small Electric-Light-and-Power Plant for Rural Homes

This little plant consists of a small gasoline engine, a dynamo, and a storage battery. The generator charges the battery, which, when the generator is not running, supplies the current for illumination and power. In case light and power are being utilized while the generator is running, the battery "floats" on the line, as indicated by the wiring diagram in the upper right-hand corner. This means that when the load is small, the battery is receiving a charge; but when the demand for current is great, the battery delivers current, thus helping the generator to do the work. This co-operation of battery and dynamo requires the dynamo to be of D.C. type. Such units are now displacing man power on the farm for milking, churning, washing, ironing, vacuum cleaning, sewing, wood-sawing, etc.



A 1.5-Billion-Electron-Volt Cosmic Ray

This picture, taken with the powerful magnet opposite page 334, shows, as does the picture opposite page 329, the results of the collision of a cosmic-ray photon (p. 620) with the nucleus of an atom of lead in the middle of the lead bar 1 centimeter thick. At least five positive electrons (the tracks turned to the right by the strong magnetic field) and twelve negative electrons (the tracks bent to the left) result from the collision. Positive electrons appear only when an atomic nucleus (p. 621) is hit. The energy of this cosmic-ray photon, as measured by the sum of the energies of all these electrons, to which it transfers both its energy and its direction, is here about 1,500,000,000 electron volts. Such cosmic-ray bullets shoot through the heads of each one of us about ten times a minute

furnished by the combination will be no larger than that furnished by a single cell, since the total resistance of the circuit has been increased in the same ratio as the total E.M.F. But if the external resistance is large, the current produced by the combination will be very much greater than that produced by a single cell. Just how much greater can always be determined by applying Ohm's law; for if there are n cells in series, and E is the E.M.F. of each cell, the total E.M.F. of the circuit is nE. Hence, if R_e is the external resistance and R_i the internal resistance of a single cell, then Ohm's law gives

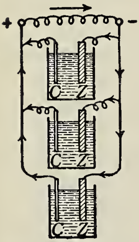


FIG. 324. Cells in parallel

$$I = \frac{nE}{R_e + nR_i}.$$

If the n cells are connected in parallel, that is, if all the coppers are connected together and all the zincs, as in Fig. 324, the E.M.F. of the combination is only the E.M.F. of a single cell, whereas the internal resistance is $1/n$ of that of a single cell, since connecting the cells in this way is simply equivalent to multiplying the area of the plates n times. The current furnished by such a combination will be given by the formula

$$I = \frac{E}{R_e + \frac{R_i}{n}}.$$

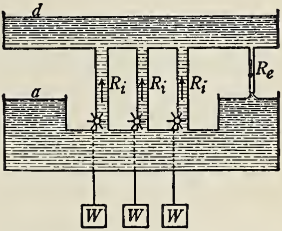


FIG. 325. Water analogy of cells in parallel

Therefore if R_e is negligibly small, as in the case of a heavy copper wire, the current flowing through it will be n times as great as that which could be made to flow through it by a single cell. Figs. 323 and 325 show by means of the water analogy why the E.M.F. of cells in series is the sum of the several E.M.F.'s, and why the E.M.F. of cells in parallel is no greater than that of a single cell. These considerations show that the rules which

should govern the combination of cells are as follows: *Connect in series when R_e is large in comparison with R_i; connect in parallel when R_i is large in comparison with R_e.* In practice the external resistance is almost always large, and hence the cells are usually connected in series.

Summary. One of the plates of a galvanic cell is eaten up, whereas some element is deposited on the other.

Polarization in the simple cell is due to an accumulation of hydrogen on the uneaten plate.

Similar cells in series give increased E.M.F., but increased internal resistance also, both in direct proportion to the number of cells.

Similar cells in parallel give no increase in E.M.F., but the internal resistance of such a group is that of one cell divided by the number of cells.

Ohm's law applied to any group of cells. The strength of the current is equal to the effective E.M.F. of the group divided by the sum of the resistances of the external circuit and of the group.

QUESTIONS AND PROBLEMS

A

1. (*a*) What are the + and − ions found in a dilute solution of H_2SO_4? (*b*) When atoms from the Zn plate of a cell are pulled into solution by the acid, what kind of charge do the Zn ions carry? What sort of charge does this leave on the Zn plate? (*c*) What do these + ions close about the Zn plate do to the + H ions of the electrolyte? (*d*) When these + H ions reach the other plate, what becomes of their + charges? (*e*) Why does a current flow through a wire connecting the two plates of a voltaic cell?

2. A certain dry cell having an E.M.F. of 1.5 volts delivered a current of 30 amperes through an ammeter having a negligible resistance. Find the internal resistance of the cell.

3. Explain the rapid weakening of a dry cell when you connect it directly to an ammeter.

4. (*a*) Diagram three wires in series and three cells in series. (*b*) If each wire has a resistance of 0.1 ohm, what is the resistance of the series? (*c*) If each cell has a resistance of 0.1 ohm, what is the internal resistance of the series?

5. (*a*) Diagram three wires in parallel (or "multiple"), and three cells in parallel. (*b*) If each wire has a resistance of 6 ohms, what is the joint resistance of the three? (*c*) If each cell has an internal resistance of 6 ohms, what is the resistance of the group?

6. What did Faraday discover concerning the influence of time and of strength of current upon the amount of chemical change produced in a cell? (See p. 342.)

B

1. (*a*) Why would you not consider using dry cells on such a telegraph line as that shown in Fig. 306? (*b*) Why can you use them on such a line as is shown opposite page 353?

2. A cell of internal resistance .05 ohm and E.M.F. 1.5 volts is connected with three resistances of 12 ohms each. Calculate the current flowing through the circuit (*a*) when the three resistances are connected in parallel; (*b*) when the three resistances are connected in series.

3. If 10 dry cells in series deliver a total current of 10 amperes and 10 other dry cells in multiple on another circuit deliver 10 amperes to the external circuit, how does the rate at which zinc is being consumed in the first group compare with the rate of consumption in the second?

4. Four new dry cells connected in series delivered a current of 2 amperes to an electromagnet whose helix had a resistance of 2.8 ohms. (*a*) What was the internal resistance of each dry cell, the E.M.F. of each cell being 1.5 volts? (*b*) If the helix consisted of 100 turns, to how many ampere turns was the magnetic effect due?

5. Ordinary No. 9 telegraph wire has a resistance of 20 ohms to the mile. What current will 100 Daniell cells in series, each of E.M.F. of 1 volt, send through 100 mi of such wire if the two relays have a resistance of 150 ohms each and the cells an internal resistance of 4 ohms each?

6. If the relays of the preceding problem had each 10,000 turns of wire in their coils, how many ampere turns would be effective in magnetizing their electromagnets?

7. (*a*) If, on the above telegraph line, sounders having a resistance of 3 ohms each and 500 turns were to be put in the place of the relays, how many ampere turns would be effective in magnetizing their cores? (*b*) Why, then, does the electromagnet of the relay have a high resistance?

Secondary Cells

Lead storage batteries. Screw two 6-by-8-inch lead plates to a half-inch strip of some insulating material, as in Fig. 326, and immerse them in a solution consisting of one part of sulfuric acid to ten parts of water. Send a current from two storage or three dry cells in series, *C*, through this arrangement, an ammeter *A* or any low-resistance galvanometer being inserted in the circuit. As the current flows, hydrogen bubbles will be seen to rise from the cathode (the plate at which the current leaves the solution), and the positive plate, or anode, will begin to turn dark brown. At the same time the reading of the ammeter will be found to decrease rapidly. The brown coating is a compound of lead and oxygen, called lead peroxide (PbO_2), which is formed when the oxygen which is liberated, precisely as in the experiment on the electrolysis of water (p. 338), acts on the lead of the plate. Now remove the batteries from the circuit by opening the key K_1, and insert an electric bell *B* in their place by closing the key K_2. The bell will ring and the ammeter *A* will indicate a current flowing in a direction opposite to that of the original current. This current will decrease rapidly as the energy which was stored in the cell by the original current is expended in ringing the bell.

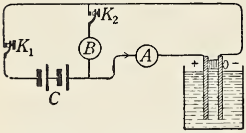


FIG. 326. The principle of the storage battery

This experiment illustrates the principle of the *storage battery*. Properly speaking, there has been no storage of *electricity*, but only a storage of *chemical energy*.

Two similar lead plates have been changed by the action of the current into two dissimilar plates, one of lead and one of lead peroxide; in other words, an ordinary galvanic cell has been formed, for any two dissimilar metals in an electrolyte constitute a primary galvanic cell. In this case the lead-peroxide plate corresponds to the copper of an ordinary cell, and the lead plate to the zinc. This cell tends to create a current opposite in direction to that of the charging current; that is, its E.M.F. pushes back against the E.M.F. of the charging cells. It was for this reason that the ammeter reading fell. When the charging current is removed, this cell

acts exactly like a *primary* galvanic cell and furnishes a current until the thin coating of peroxide is used up. For those who have had chemistry we may state that the chemical action in the lead storage cell is expressed by the equation

$$2\,PbSO_4 + 2\,H_2O \underset{\longleftarrow \text{discharging}}{\overset{\text{charging} \longrightarrow}{\rightleftharpoons}} PbO_2 + Pb + 2\,H_2SO_4.$$

Commercial lead storage batteries. The only important difference between a commercial storage cell (Fig. 327) and the

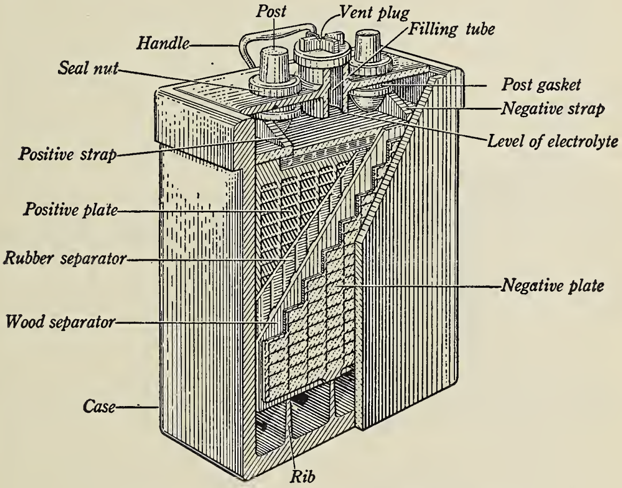


FIG. 327. Section of a commercial storage cell

one which we have here used is that the former is provided in the making with a much thicker coat of the "active material" (lead peroxide on the positive plate and a porous, spongy lead on the negative) than can be formed by a single charging such as we used. This material is pressed into slots, squares, or other openings in the plates, as is shown in Fig. 327. The

E.M.F. of the lead storage cell is about 2 volts. Since the plates are always very close together and may be given any desired size, the internal resistance is usually small, so that the currents furnished may be of very large amperage.

The usual efficiency of the lead storage cell is about 75 per cent; that is, only about three fourths as much electrical energy can be obtained from it as is put into it.

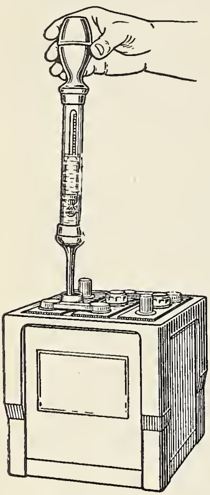


FIG. 328. Taking the specific gravity of the electrolyte

The extent to which a lead storage cell is charged is determined by taking the specific gravity of its electrolyte (Fig. 328). Since water is formed while the cell is discharging, the proportion of water (specific gravity 1) to sulfuric acid (specific gravity 1.8) is increasing. Thus the specific gravity of the mixture is decreasing. The specific gravity of a fully charged cell is about 1.3; that of a discharged cell may be as low as 1.15. In common practice these limits are called 1300 and 1150.

We are all familiar with the uses of storage cells in the automobile. In some country districts farmers use them for lighting purposes, recharging them with a dynamo driven by a gasoline engine. (See opposite page 374.)

The outside of the lead storage battery should be kept dry and clean to prevent leakage of current. Since ordinary water may contain metal salts in solution, causing local action, it is necessary to add carefully distilled, or purified, water at intervals, enough to keep the plates just covered. When the battery is new, metal contacts should be carefully smeared with pure vaseline to prevent the acid electrolyte from corroding terminals, connections, and the like. The condition of the battery should be tested frequently with a hydrometer. If it is found to be badly discharged, it should

be charged immediately, as the plates are injured when the battery remains some time in a discharged state.

Nickel-iron storage batteries. Thomas A. Edison (see opposite page 476) developed and perfected the nickel-iron caustic-potash storage cell. The electrolyte is a 21 per cent solution of caustic potash in water to which is added a small amount of lithium hydroxide. The negative plates contain iron powder securely held in perforated flat rectangular capsules, and the positive plates contain nickel peroxide in perforated cylindrical containers. For equal capacities the Edison cell weighs about half as much as the lead cell, and it will stand a remarkable amount of electrical and mechanical abuse. The E.M.F. is about 1.2 volts. Because of large internal resistance these cells are not adapted to starting automobiles; their especial field is as a source of motive power for electric trucks and battery-driven streetcars. In efficiency the Edison cell is a little below the lead cell.

Summary. **The energy of an electric current does work upon a storage battery in charging it, thus storing potential energy in chemical form.**

When a storage battery discharges, the stored chemical energy changes back to electrical energy.

QUESTIONS AND PROBLEMS

1. The lead-peroxide plate and the nickel-peroxide plate are both called the *positives*. What is the relation of the charging current to these plates?

2. (*a*) In charging a storage battery is it better to say that the current passes *into* the cell or *through* it? (*b*) What is *stored*?

3. (*a*) If an automobile is equipped with 6-volt lamps, how many lead storage cells must be on the car? (*b*) Are these cells in series or multiple (parallel)?

4. If you attempted to charge a storage battery with a current having the same voltage as the battery, what would be the result? Explain.

Heating Effects of the Electric Current

Heat developed in a wire by an electric current. Touch the terminals of two or three dry cells in series to a piece of No. 40 iron or German-silver wire and shorten the length of wire between these terminals to $\frac{1}{4}$ in. or less. The wire will be heated to incandescence and probably melted.

The experiment shows that in the passage of the current through the wire the energy of the electric current is transformed into heat energy. The electrical energy used up when a current flows between points of given P.D. may be spent in a variety of ways. For example, it may be spent in producing chemical separation, as in the charging of a storage cell; it may be spent in doing mechanical work, as in running an electric motor; or it may be spent wholly in heating the wire, as was the case in the experiment. It will always be expended in this last way when no chemical or mechanical changes are produced by it.

Energy relations of the electric current. We found in Chapter VII that energy expended on a water turbine is equal to the quantity of water passing through it times the difference in level through which the water falls, or that the *power* (rate of doing work) is the product of the *fall in level* and the *current strength.* In just the same way it is found that when a current of electricity passes through a conductor, the power, or rate of doing work, is equal to the *fall in potential* between the ends of the conductor times the *strength of the electric current.* If the P.D. is expressed in volts and the current in amperes, the power is given in watts, and we have

$$\text{Volts} \times \text{amperes} = \text{watts}.$$

This relationship follows simply as a result of the way in which the units are chosen. The *energy* of the electric current is usually measured in kilowatt-hours.

A kilowatt-hour is the quantity of energy furnished in one hour by a current whose power, or rate of expenditure of energy, is a kilowatt.

Applications of heating effects. Probably most of the electric devices in your home depend in some essential way on the heating effects of current. Electric toasters, percolators, irons, heaters, and so on are in principle nothing but a few coils of high-resistance wire which become very hot when a current is sent through them. These coils are for practical reasons arranged differently in the different appliances, but in all but detail these devices and many others are alike.

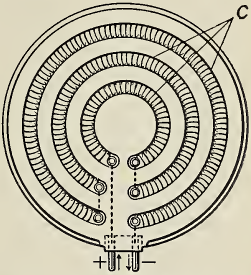


FIG. 329. Electric heater (coils of nichrome wire)

Amount of heat developed by a current. Since 1 calorie is equal to 42,000,000 ergs (p. 212), 1 watt (10,000,000 ergs per second) develops in one second .24 calorie. Therefore the number of calories, H, developed in t seconds by a current of I amperes between two points whose P.D. is E volts is expressed by the equation

$$H = .24\,EIt.$$

Since from Ohm's law $E = IR$,

$$H = .24\,I^2Rt,$$

or *the heat generated in a conductor is proportional to the time, to the resistance, and to the square of the current.*

[**Short circuits and fuses.** When the two wires leading to a lamp in some way touch each other without insulation, so that the current flows from one to the other without going through the lamp, we say that the lamp is short-circuited. The resistance is much reduced, and thus the current proportionately increased. Since the heating effect depends on the square of the current and only on the first

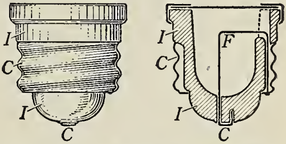


FIG. 330. Plug fuses. The fusible wire F is surrounded by fireproof material I

power of the resistance, the current is the more important factor, and the wires in the circuit will become very hot.

For example, suppose the resistance of the lamp is 99 ohms and that of the lead wires 1 ohm, the total resistance in the circuit being 100 ohms. If the circuit has a potential across it of 100 volts, the current will be 1 ampere by Ohm's law. The heat developed in the circuit per second will be $.24 \times 1 \times 100 = 24$ calories. Now if the potential remains the same, the short circuit will reduce the resistance to 1 ohm and thus increase the current to 100 amperes. The total heating effect per second will now be $.24 \times 10{,}000 \times 1 = 2400$ calories, one hundred times as great as before. Very often this heat would be sufficient either to melt the wire somewhere in the walls of the house or perhaps to burn out the dynamo at the power plant. To prevent this *fuses* are inserted in the circuit. They contain a short piece of soft metal which melts when the current through it is greater than a given amount. When the circuit is overloaded, the fuse always melts before any damage can be done, thus breaking the circuit. When the short circuit has been repaired, the fuse may easily be replaced.

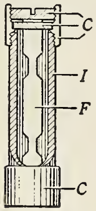


FIG. 331. Cartridge fuse. Brass contacts are shown at C. The fusible metal F is enclosed in insulating material

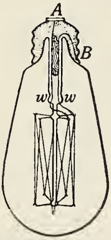
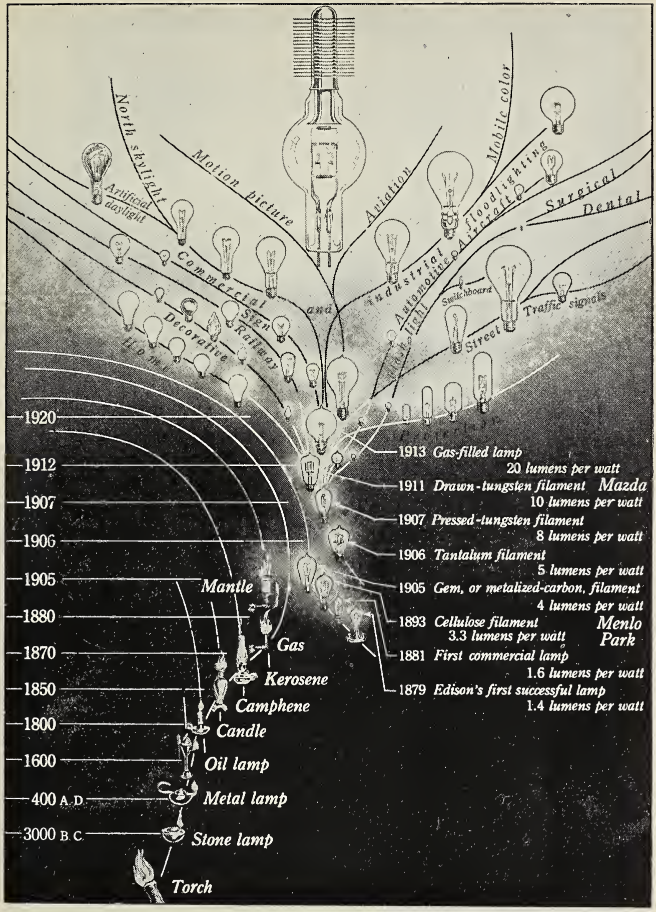


FIG. 332. The tungsten vacuum lamp

Incandescent lamps. The ordinary incandescent lamp (Fig. 332) consists of a tungsten filament heated to incandescence by an electric current.

Since the filament would quickly burn up in air, it was formerly placed in a bulb exhausted to a high vacuum. When in use it slowly vaporized, depositing a dark, mirrorlike coating of metal upon the inner surface of the bulb. The lead-in wires were soldered one to the base A of the socket and the other to its rim B, these



History of Artificial Lighting from the Early Torch to the Modern Incandescent Lamp

Note how little artificial light man had used up to 1850; then turn to the next page. (Courtesy of the General Electric Company)

Baseball Field Floodlighted with "Novalux" Projectors
Crosley Field, Cincinnati, Ohio. (Courtesy of the General Electric Company)

being the electrodes through which the current entered and left the lamp. The wires w, w, sealed into the walls of the bulb, had the same coefficient of expansion as the glass, to prevent leakage of air.

By filling the bulb with argon* the present very efficient form of the tungsten lamp is obtained (Fig. 333). The long filament is wound into an exceedingly fine spiral to minimize heat radiation. As we have already learned (p. 235), the presence of gas retards evaporation; hence because of the argon the filament may be raised to 2400° C., a higher temperature than is permissible in a vacuum. A greatly increased candle power results from the slight increase in current. Moreover, the convection currents in the gas-filled lamp cause the mirror due to vaporization to form near the top of the globe, where it does not obscure the intensity of the light. Gas-filled lamps have very largely replaced the high-vacuum lamps. (See opposite page 384.)

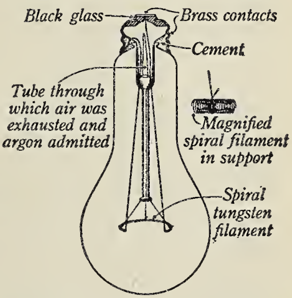


FIG. 333. Gas-filled lamp with fine spiral filament

Incandescent lamps are usually grouped in parallel (or "multiple") on a circuit that maintains a potential difference of about 110 volts between the terminals of the lamps. Engineers measure the amount of light they give off either in candle power or in *lumens*, a lumen being the amount of light a standard candle throws on a square foot of surface a foot away. A standard candle thus gives 4π, or about 12.6 lumens. The rate of consumption of energy is from 1 to 1.25 watts per candle power, or 8 to 12 lumens per watt, for the smaller sizes. The larger sizes of gas-filled lamps, such as those used for street-lighting, consume only 0.6 watt per

* A gas which does not enter into chemical combination. There are about 8 cubic centimeters of argon in each liter of ordinary air.

candle power. (See opposite page 384.) Tungsten filaments, being operated at a much higher temperature than is possible with the now almost obsolete carbon filament, have an efficiency nearly three times as great.

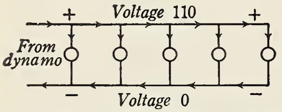


FIG. 334. Incandescent lamps are wired in parallel

A customer usually pays for his light by the kilowatt-hour (p. 382). The rate at which energy is consumed by a lamp carrying $\frac{1}{4}$ ampere at 100 volts is 25 watts. Two such lamps running for 4 hours would, therefore, consume $2 \times 4 \times 25 = 200$ watt-hours = .200 kilowatt-hour. The energy is measured and recorded on a *recording watt-hour meter* (Fig. 359).

Today the production of incandescent lamps is enormous. Under the patents of one organization alone there are manufactured 3000 lamps every minute of every working day throughout the year.

FIG. 335. The arc light

The carbon arc light. When two carbon rods are placed end to end in the circuit of a powerful electric generator, the carbon about the point of contact is heated red-hot. If then the ends of the carbon rods are separated one-fourth inch or so, the current will still continue to flow, for a conducting layer of incandescent vapor, called an *electric arc*, is produced between the poles. The appearance of the arc is shown in Fig. 335. At the + pole a hollow, or crater, is formed in the carbon, and the − carbon becomes cone-shaped, as in the figure. The carbons are consumed at the rate of about an inch an hour, the + carbon wasting away about twice as fast as the − one. The light comes chiefly from the + crater, where the temperature is about 3700° C. (6800° F.), the highest attainable by man. All known substances are volatilized in the electric arc.

The light of the arc lamp is due to the intense heat developed on account of resistance, not to actual combustion, or burning.

The powerful and efficient arc lamp is now practically obsolete except for spotlights, motion-picture machines, and searchlights.

The Cooper-Hewitt mercury arc lamp. The Cooper-Hewitt mercury arc lamp (Fig. 336) differs from the carbon arc lamp in that the incandescent body is a long column of mercury vapor instead of an incandescent solid. The lamp consists of an exhausted tube 3 or 4 feet long, the positive electrode at the top being a plate of iron, and the negative electrode at the bottom a small quantity of mercury. Before the lamp begins to burn, the space within it is an almost perfect vacuum, through which the difference in potential at the terminals is unable to send a current. To start the lamp the lower end is tilted upward and then immediately lowered. This forms a momentary continuous conducting column of mercury, which on breaking establishes an arc the heat of which fills the tube with the vapor of mercury. A long mercury-vapor arc is thus formed, which stretches from terminal to terminal in the tube. This arc emits a very brilliant light, but it is almost entirely wanting in red rays. The strength of its actinic rays makes it especially valuable in photography. Its commercial efficiency is about .6 watt per candle power. Cooper-Hewitt lamps having quartz tubes are used for sterilizing purposes because of the powerful ultraviolet rays which the quartz transmits.

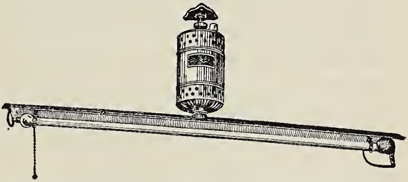


FIG. 336. The Cooper-Hewitt mercury arc lamp

The neon lamp. The lamps used in most advertising signs today are of the so-called gas-glow type. They consist of tubes containing neon, mercury vapor, or helium, or mixtures of these gases at pressures of from 1 to 10 millimeters of mercury. When a P.D. of 8000 to 12,000 volts is applied to the electrodes set in the ends of the tubes, a continuous

electrical discharge of a few thousandths of an ampere takes place through the gas. This discharge causes the gases to glow with a characteristic color, neon lamps being reddish, mercury-vapor green, and helium white. Different shades are obtained by mixing the gases or by painting the glass tubes in which they are contained. The neon lamp has an efficiency about equal to that of the best incandescent lamps. It gives a more uniform distribution of light, but is objectionable for some uses because of its color. The white helium lamp is unsatisfactory for general use since its efficiency is only about one quarter that of the incandescent lamp.

[**The sodium-vapor lamp.** This is a variation of the gas-filled lamp. The electrical discharge, carried at first by a small amount of neon at a pressure of about 1.5 millimeter, soon heats the lamp to a temperature of about 220° C. A small amount of metallic sodium contained in the bulb becomes vaporized by the heat and fills the lamp, giving off the characteristic yellow sodium color. The lamp was developed in the laboratory soon after the war, but could not be used commercially because the sodium attacked the glass bulb chemically. It was not until 1930 that a transparent phosphate glaze was developed, which resisted the action of the sodium and made commercial production of the lamp possible.

[The sodium lamp has been found particularly useful in street-lighting, where the monochromatic yellow color is not a disadvantage. It has an efficiency two to three times as great as that of the best filament lamps, consuming as little as .2 watt per candle power.

Summary. **Electrical power is measured in watts. 746 watts = 1 horse-power. Watts = volts × amperes.**

Electrical energy is measured in kilowatt-hours.

The number of calories of heat developed by the electric current in any number of seconds = .24 I^2Rt.

The heating effects of a current are utilized in many household electric appliances.

The sodium-vapor lamp is the most efficient yet developed.

QUESTIONS AND PROBLEMS

A

1. If an automobile storage battery has an E.M.F. of 6 volts and furnishes a momentary current of 200 amperes in starting the engine, what is its power, or rate of expenditure of energy, (*a*) in watts? (*b*) in kilowatts? (*c*) in horsepower?

2. If one of the wire loops in a tungsten lamp is short-circuited, what effect will this have (*a*) on the amount of current flowing through the lamp? (*b*) on the brightness of the filament? (*c*) on the life of the lamp?

3. (*a*) What is meant by a 104-volt lamp? (*b*) What would happen to such a lamp if the P.D. at its terminals amounted to 550 volts? (*c*) Trolley cars are usually furnished with current at about 550 volts; how would you use 110-volt lamps on such a circuit?

4. How many 25-watt incandescent lamps, connected in parallel, might be used at the same time on a 110-volt house-lighting circuit capable of furnishing a current of 10 amperes?

5. How long can you burn one 25-watt lamp in your home for a cent at 5 cents per kilowatt-hour?

6. A small arc lamp requires a current of 5 amperes and a difference of potential between its terminals of 45 volts. What resistance must be connected in series with it in order to use it on a 110-volt circuit?

B

1. A 50-volt carbon lamp carrying 1 ampere has about the same candle power as a 100-volt carbon lamp carrying $\frac{1}{2}$ ampere. Explain why.

2. A very common electric lamp used in our homes is marked 25 watts and carries about $\frac{1}{4}$ ampere. One fresh dry cell on short circuit will deliver 30 or more amperes. Will the cell light the lamp? (Prove your answer is right by using the data given.)

3. An electric flatiron taking 5 amperes from a 110-volt circuit is used for 25 min. (*a*) What is its resistance? (*b*) How many watts does it require? (*c*) If the rate is 5 cents per kilowatt-hour, what is the cost of the electrical energy used?

4. The resistance of a certain water-heating coil is 20 ohms, and when connected to the house circuit it carries 5 amperes. How many minutes will it take this coil to heat 480 g of water from 10° C. to 100° C.?

5. A certain kind of electric toaster takes 5 amperes at 110 volts. It will make two pieces of toast at once in 3 min. (*a*) At what horsepower rate does the toaster convert electrical energy into heat energy? (*b*) At 5 cents per kilowatt-hour what does it cost to make 12 pieces of toast?

6. An electric soldering iron allows 5 amperes to flow through it when connected to an E.M.F. of 110 volts. What will it cost, at 5 cents per kilowatt-hour, to operate the iron 6 hr per day for 5 days?

7. A current of electricity through a coil of wire having a resistance of 10 ohms heated 1000 g of water from 15° C. to 61.08° C. in 5 min. What was the strength of the current?

8. At a cost of 4 cents per kilowatt-hour how much will it cost per week of 48 hr to run a motor having an average load of 35 H.P. and an average efficiency of 85 per cent? (One horsepower = 746 watts.)

CHAPTER XV

Induced Currents

The Principle of the Dynamo and Motor

Current induced by a magnet. We have seen something of the vast number of ways in which electricity increases our comfort and does much of our work for us. But most of the applications of electricity we have studied depend upon sources of plentiful current. The chemical sources we have discussed would be wholly inadequate to supply a fraction of the electricity we use every day. We have, however, practically unlimited sources of mechanical energy in waterfalls, in steam and gasoline engines, etc. In 1831 the great Michael Faraday made a discovery which showed how this mechanical energy might be transformed into electrical energy, the discovery on which all modern power plants are based. Let us repeat his experiment for ourselves.

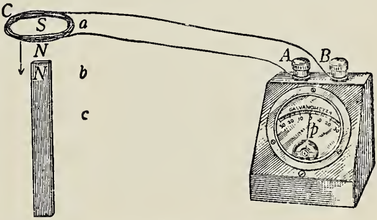


FIG. 337. Induction of electric currents by magnets

Wind 100 turns of No. 22 copper wire into a coil C (Fig. 337) about $2\frac{1}{2}$ in. in diameter. Connect this coil into circuit with a sensitive D'Arsonval galvanometer, or even a simple detector made by suspending between the poles of a strong horseshoe magnet, with No. 40 copper wire, a coil of 200 turns of No. 30 copper wire (Fig. 345). Thrust the coil C suddenly over the N pole of a strong magnet. The deflection of the pointer p of the galvanometer will indicate a momentary current flowing through the coil. Hold the coil stationary over the magnet. The pointer will be

found to come to rest in its natural position. Now remove the coil suddenly from the pole. The pointer will move in a direction opposite to that of its first deflection, showing that a reverse current is now being generated in the coil.

We learn, therefore, that *a current of electricity may be induced in a conductor by causing the latter to move through a magnetic field*, though a magnet has no such influence upon a conductor which is at rest with respect to the field. We shall see that all the various kinds of dynamos, or generators, are fundamentally nothing but devices for moving a conductor through a magnetic field and drawing off the current thus produced.

Direction of induced current; Lenz's law. In order to find the *direction* of the induced current, apply a very small P.D. from a galvanic cell to the terminals *A* and *B* (Fig. 337), and note the direction in which the pointer moves when the current enters, say, at *A*. This will at once show in what direction the current was flowing in the coil *C* when it was being thrust over the *N* pole. Apply the right-hand rule (p. 345) to the coil to find which was the *N* and which the *S* face of the coil when the induced current was flowing through it. It will be found that if the coil was being thrust over the *N* pole of the magnet, the current induced in the coil was in such a direction as to make its lower face an *N* pole during the downward motion (Fig. 338 (*a*) and (*b*)) and an *S* pole during the upward motion (Fig. 338 (*c*) and (*d*)). In the first case the repulsion of the *N* pole of the magnet and the *N* pole of the coil tended to *oppose* the motion of the coil while it was moving from *a* to *b*, and the attraction of the *N* pole of the magnet and the *S* pole of the coil tended to oppose the motion while it was moving from *b* to *c*. In the second case the repulsion of the two *N* poles tended to oppose the motion from *c* to *b*, and the attraction between the *N* pole of the magnet and the *S* pole of the coil tended to oppose the upward motion from *b* to *a*. *In every case, therefore, the motion is made against an opposing force.*

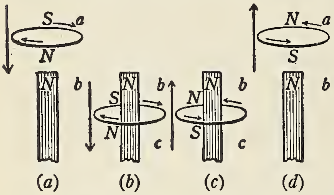
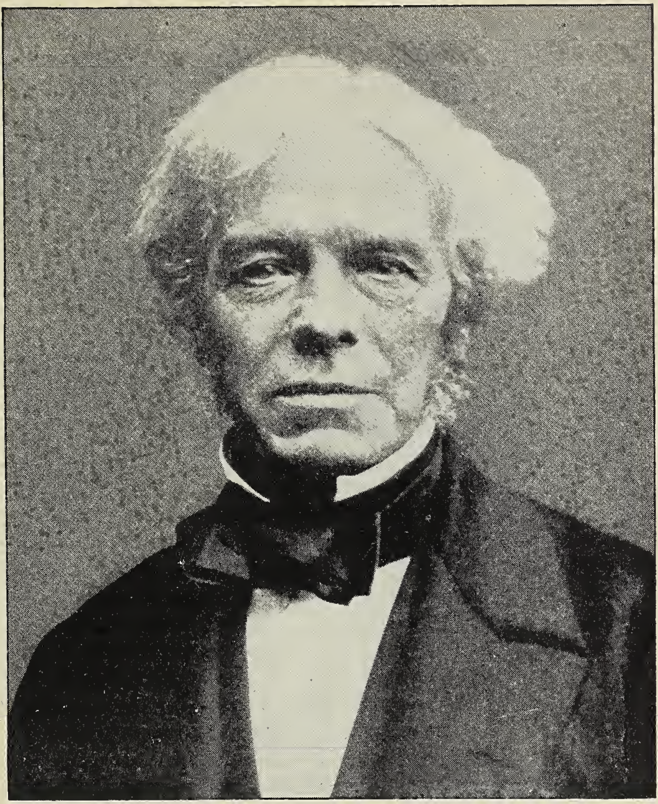
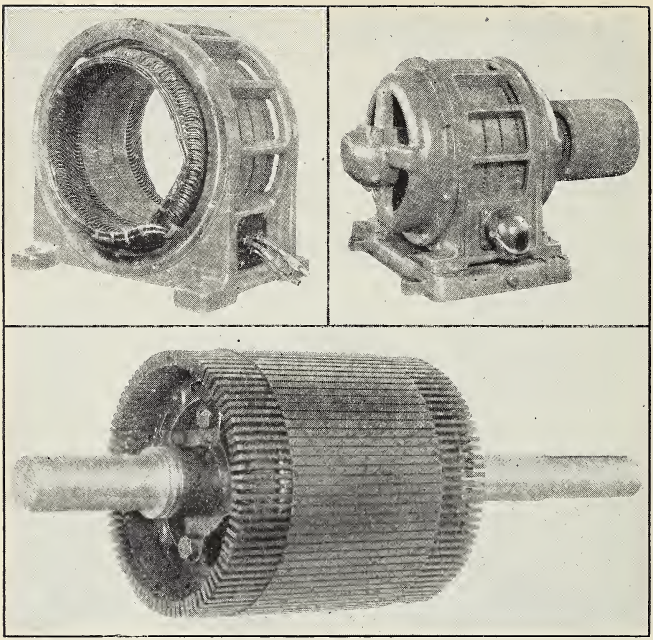


FIG. 338. Illustrating Lenz's law



Michael Faraday (1791–1867)

Famous English physicist and chemist and one of the most gifted of experimenters; son of a poor blacksmith; apprenticed at the age of thirteen to a London bookbinder, with whom he worked nine years; applied for a position in Sir Humphry Davy's laboratory at the Royal Institution in 1813; became director of this laboratory in 1825; discovered electromagnetic induction in 1831; made the first dynamo; discovered in 1833 the laws of electrolytic deposition, now known as Faraday's laws. The farad and the microfarad, the practical units of electrical capacity, are named in his honor



Induction Motor

One of the most familiar of the more recent applications of the great principle of induction discovered by Faraday is the induction motor, which has come into extensive use in both large and small sizes. The particular one here shown is known as the squirrel-cage form, in which there is no electrical connection between the stator (the stationary part) and the rotor (the revolving part). The stator is wound on a laminated core like the stator of a dynamo, and the rotor consists of copper bars laid in a slotted, laminated core, their ends being joined to copper rings, one at each end. The bars are therefore in parallel. The alternating current applied to the stator windings develops a magnetic field which rotates around the iron ring of the stator. This is equivalent to a set of magnetic poles mechanically rotated around the rotor. The magnetic lines of force which therefore cut across the copper bars of the rotor generate in them an E.M.F. which causes a current to flow in the copper system of the rotor. The rotating field reacts with the field produced by the current in the conductors of the rotor so as to cause the rotor to be dragged around after the rotating field

From these experiments, and others like them, we arrive at the following law: *Whenever a current is induced by the relative motion of a magnetic field and a conductor, the direction of the induced current is always such as to set up a magnetic field which opposes the motion.* This is Lenz's law. This law might have been predicted at once from the principle of the conservation of energy; for this principle tells us that since an electric current possesses energy, such a current can appear only through the expenditure of mechanical work or of some other form of energy.

Condition necessary for an induced E.M.F. Hold the coil in the position shown in Fig. 339, and move it back and forth *parallel* to the magnetic field, that is, parallel to the line *NS*. No current will be induced.

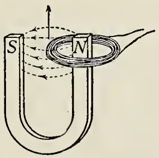


FIG. 339. Currents induced only when conductor *cuts* lines of force

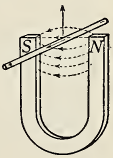


FIG. 340. E.M.F. induced whenever a straight conductor cuts magnetic lines

By experiments of this sort it is found that an E.M.F. is induced in a coil only *when the motion takes place in such a way as to change the total number of magnetic lines of force which are enclosed by the coil.* Or, to state this rule in more general form, *an E.M.F. is induced in any element of a conductor when, and only when, that element is moving in such a way as to cut magnetic lines of force.**

It will be noticed that the first statement of the rule is included in the second, for whenever the number of lines of force which pass through a coil changes, some lines of force must cut across the coil from the inside to the outside, or vice versa.

* If a strong electromagnet is available, these experiments are more instructive if performed, not with a coil, as in Fig. 339, but with a straight rod (Fig. 340) to the ends of which are attached wires leading to a galvanometer. Whenever the rod moves parallel to the lines of magnetic force there will be no deflection, but whenever it moves across the lines the galvanometer needle will move at once.

The principle of the electric motor. Having found how mechanical energy can be transformed into electrical energy, we are now curious as to how to reverse the process. To take the energy of a waterfall to a distant factory by mechanical means would be impracticable; but if we can change it into electrical form for the journey and then back into mechanical form at the factory, we can carry it a great distance. We have observed the effect of a current on a magnet suspended freely near it. Newton's third law tells us that the magnet should exert an equal force on the wire which carries the current. Let us perform an experiment to test our theory.

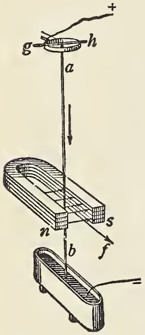


FIG. 341. The principle of the electric motor

Attach a vertical wire *ab* rigidly to a horizontal wire *gh*, and support the latter by a ring or other metallic support, in the manner shown in Fig. 341, so that *ab* is free to oscillate about *gh* as an axis. Dip the lower end of *ab* into a trough of mercury. When a magnet is held in the position shown and a current from a dry cell is sent down through the wire, the wire will instantly move in the direction indicated by the arrow *f*, namely, at right angles to the direction of the lines of magnetic force. Reverse the direction of the current in the wire. The direction of the force acting on the wire will be found to be reversed also.

We learn, therefore, that *a wire carrying a current in a magnetic field tends to move in a direction at right angles both to the direction of the field and to the direction of the current.* This fact underlies the operation of all electric motors.

The motor and dynamo rules. A convenient rule for determining whether the wire *ab* (Fig. 341) will move forward or back in a given case may be obtained as follows: If the field of a magnet alone is represented by Fig. 342, and that due to the current* alone by Fig. 343, then the resultant field

* The cross in the conductor of Fig. 343, representing the tail of a retreating arrow, indicates that the current flows away from the reader. A dot, representing the head of an advancing arrow, would indicate a current flowing toward the reader.

when the current-bearing wire is placed between the poles of the magnet is that shown in Fig. 344; for the strength of the field above the wire is now the sum of the two separate fields, and the strength below it is their difference. Now Faraday thought of the lines of force as acting like stretched rubber bands. This would mean that the wire in Fig. 344 would be pushed *down*. *The motor rule* may be stated thus:

A current in a magnetic field tends to move away from the side on which its lines are added to those of the field.

The dynamo rule follows at once from the motor rule and Lenz's law. Thus, when a wire is moved through a magnetic

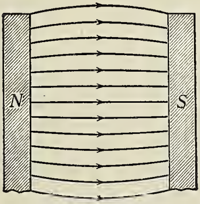


FIG. 342. Field of magnet alone

FIG. 343. Field of current alone

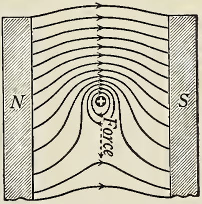


FIG. 344. Field of magnet and current

field, the current induced in it must be in such a direction as to oppose the motion; therefore *the induced current will be in such a direction as to increase the number of lines on the side toward which it is moving.*

Strength of the induced E.M.F. The strength of an induced E.M.F. is found to depend simply upon *the number of lines of force cut per second* by the conductor, or, in the case of a coil, upon the *rate of change* in the number of lines of force which pass through the coil. The strength of the current which flows is then given by Ohm's law; that is, it is equal to the induced E.M.F. divided by the resistance of the circuit. The number of lines of force which the conductor cuts per second may always be determined if we know the velocity of the conductor and the strength of the magnetic field through which it moves. For it will be remembered that,

according to the convention mentioned on page 303, a field of unit strength is said to contain one line of force per square centimeter, a field of 1000 units strength 1000 lines per square centimeter, etc. In a conductor which is cutting lines at the rate of 100,000,000 per second there is an induced E.M.F. of 1 volt.* The reason why we used a coil of 100 turns instead of a single turn in the experiment on page 391 was that by thus making the conductor in which the current was to be induced cut the lines of force of the magnet 100 times instead of once, we obtained 100 times as strong an induced E.M.F., and therefore 100 times as strong a current for a given resistance in the circuit.

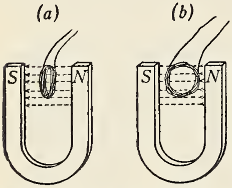


FIG. 345. Direction of currents induced in a coil rotating in a magnetic field

Currents induced in rotating coils. Make a 400-turn or 500-turn coil of No. 28 copper wire small enough to rotate between the poles of a horseshoe magnet, and connect it into the circuit of a galvanometer, precisely as on page 391. With the coil in the position of Fig. 345 (*a*), rotate it suddenly clockwise (the observer looking down from above) through 180°. A strong deflection of the galvanometer will be observed. Rotate it through the next 180° back to the starting point. An opposite deflection will be observed.

The arrangement is a *dynamo* in miniature. During the first half of the revolution (see Fig. 345 (*b*)) the wires on the right side of the loop were cutting the lines of force in one direction, while the wires on the left side were cutting them in the opposite direction. A current was being generated down on the right side of the coil and up on the left side (see dynamo rule). It will be seen that both currents flow around the coil in the same direction. The induced current is strongest when the coil is in the position shown in Fig. 345 (*b*), because there the lines of force are being cut most rapidly.

* This may be considered as *the scientific definition of the volt*, convenience alone having dictated the legal definition given on page 373.

Just as the coil is moving into or out of the position shown in Fig. 345 (*a*), its edges are moving *parallel* to the lines of force; hence no current is induced, since no lines of force are being cut. As the coil moves through the last 180° of its revolution, both sides are cutting the same lines of force as before, but they are cutting them in an opposite direction; hence the current generated during this last half is opposite in direction to that of the first half.*

Summary. An induced E.M.F. is produced in a conductor when it cuts or is cut by magnetic lines of force.

The induced voltage is proportional to the rate of cutting of magnetic lines.

Lenz's law. The direction of the induced E.M.F. is always such as to tend to oppose the motion (or any sort of change) producing it.

A conductor carrying a current in a magnetic field tends to move in a direction at right angles both to the direction of the field and to the direction of the current.

The motor rule. A current in a magnetic field tends to move away from the side on which its lines are added to those of the field.

The dynamo rule. The direction of the induced E.M.F. is such as to oppose the motion, that is, to thicken the magnetic lines on the side toward which the conductor is moving.

QUESTIONS AND PROBLEMS

A

1. Under what conditions may an electric current be produced by a magnet?

2. State Lenz's law, and show how it follows from the principle of the conservation of energy.

3. A coil is thrust over the *S* pole of a magnet. Is the direction of the induced current clockwise or counterclockwise as you look down upon the pole?

4. How many lines of force must be cut per second to induce 10 volts?

* A laboratory experiment on the principles of induction should be performed at about this point. See, for example, Experiment 47 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

5. If a coil of wire is rotated about a vertical axis in the earth's field, an alternating current is set up in it. In what position is the coil when the current changes direction?

B

1. Can the number of lines of force within a closed coil of wire be increased or decreased without the lines being cut by the wire? Explain.

2. A ship having an iron mast is sailing east. (*a*) In what direction is the E.M.F. induced in the mast by the earth's magnetic field? (*b*) If a wire is brought from the top of the mast to its bottom, no current will flow through the circuit. Why?

3. A current is flowing from top to bottom in a vertical wire. In what direction will the wire tend to move on account of the earth's magnetic field?

Dynamos and Motors

A simple alternating-current dynamo. In spite of the enormous power produced by a modern generator, the principle on which it works is based on simple laws. Nothing of importance has been added, except more elaborate machinery, since Faraday in 1831 worked out the laws.

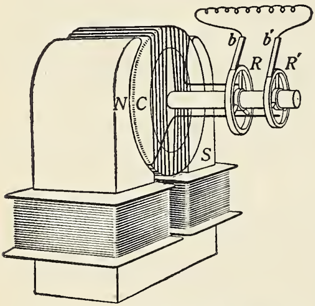


FIG. 346. Drum-wound armature

The development of the modern industry dates from September 4, 1882, when the first central electric generating station was started in New York City and furnished energy for lighting a small area in downtown Manhattan. With this start our present epoch in electricity began, for the basic principles were the same as those used today by electric light and power companies.

The simplest form of commercial dynamo consists of a coil of wire so arranged as to rotate continuously between the poles of a powerful electromagnet (Fig. 346).

In order to make the magnetic field in which the conductor is moved as strong as possible, the coil is wound upon an iron core *C*. This greatly increases the total number of lines of magnetic force which pass between *N* and *S*, for instead of an air path the core offers an iron path, as shown in Fig. 347.

The rotating part, consisting of the coil with its core, is called the *armature*. One end of the coil is attached to the insulated metal ring *R* (Fig. 346), which is attached rigidly to the shaft of the armature and therefore rotates with it, and the other end of the coil is attached to a second ring *R′*. The brushes *b* and *b′*, which constitute the terminals of the external circuit, are always in contact with these rings (Fig. 346).

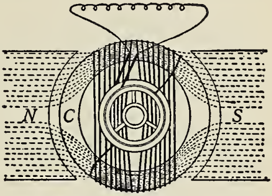


FIG. 347. End view of drum armature

As the armature coil is forced to rotate, an induced current passes through the circuit. This current reverses direction as often as the coil passes through the position shown in Fig. 347, that is, the position in which the conductors are moving *parallel* to the lines of force; for at this instant the conductors which were moving up begin to move down, and those

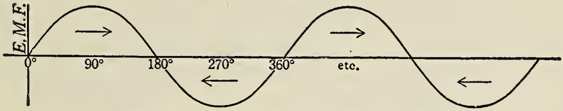


FIG. 348. Curve of alternating E.M.F.

which were moving down begin to move up. The current reaches its maximum value when the coils are moving through a position 90° farther on, for then the lines of force are being cut most rapidly by the conductors on both sides of the coil. Such a current is called an *alternating* current. Two changes in direction, or one complete revolution of the arma-

ture, make up a *cycle*. These facts are graphically represented by the curve of E.M.F.'s (Fig. 348).

The multipolar alternator. For most commercial purposes it is found desirable to have 120 or more alternations of current per second, that is, 60 or more cycles. This would require too high a speed of rotation with two-pole machines like those sketched in Figs. 346 and 347. Hence commercial alternators are commonly built with a large number of poles, alternately N and S, arranged around the circumference of a circle in the manner shown in Fig. 349. These poles are excited by a *direct* current. The dotted lines represent the direction of the lines of force through the iron. It will be seen that the coils which are passing the N poles have induced currents set up in them the direction of which is opposite to that of the currents which are induced in the conductors which are passing across the S poles. Since, however, the direction of winding of the armature coils changes between each two poles, all the inductive effects of all the poles are added in the coil and constitute at any instant one single current flowing around the complete circuit in the manner indicated

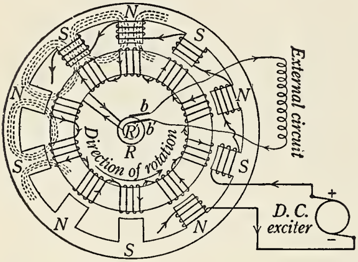


FIG. 349. Diagram of alternating-current dynamo

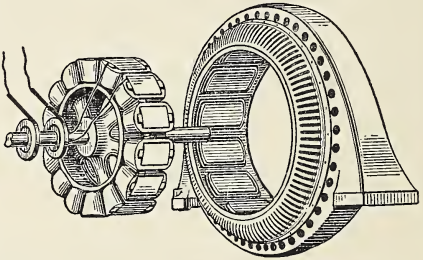


FIG. 350. A single-phase alternating-current generator with revolving poles partially removed

by the arrows in the diagram. This current reverses direction at the instant at which all the coils pass the midway points between the N and S poles. The number of alternations per second is equal to the number of poles multiplied by the number of revolutions per second. Half the number of alternations is the number of cycles. Fig. 348 represents four alternations, or two cycles. The number of cycles per second is called the *frequency*. The field magnets N and S of such a dynamo are excited by a direct current from some other source. In principle it is of course of no importance whether the fixed magnets N and S are stationary (as in Fig. 349) and the armature coils revolve inside, or whether the rotor carries the magnets and the armature coils are stationary on the outer frame (as in Fig. 350). The latter arrangement has practical advantages and is the more common arrangement in large installations. Alternators of 5000-kilowatt capacity (nearly 7000 horsepower) have been built to run at the unusually high speed of 3600 revolutions per minute. Alternators of lower speed but of very much greater capacity are common. (See opposite page 349.)

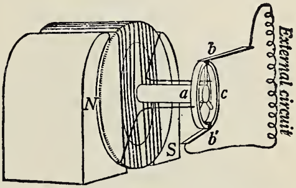


FIG. 351. The simple commutator

The principle of the commutator. By the use of a so-called *commutator* it is possible to transform a current which is alternating in the coils of the armature to one which always flows in the same direction through the external portion of the circuit. The simplest possible form of such a commutator is shown in Fig. 351. It consists of a single metallic ring which is split into two equal insulated semicircular segments a and c. One end of the rotating coil is soldered to one of these semicircles, and the other end to the other semicircle. Brushes b and b' are set in such positions that they lose contact with one semicircle and make contact with the other at the instant at which the current changes direction in the

armature. The current, therefore, always passes out to the external circuit through the same brush. Although a current from such a coil and commutator as that shown in the figure would always flow in the same direction through the external circuit, it would be of a pulsating rather than a steady character, for it would rise to a maximum and fall again to zero twice during each complete revolution of the armature. This effect is avoided in the commercial direct-current dynamo by building a commutator of a large number of segments instead of two, and connecting each to a portion of the armature coil in the manner shown in Fig. 352. The result of using a simple split-ring commutator is shown graphically in Fig. 353.

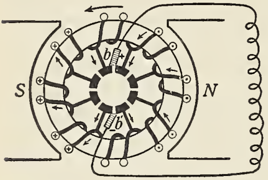


FIG. 352. A two-pole direct-current dynamo with ring armature

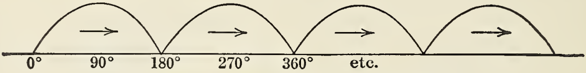


FIG. 353. Curve of commutated E.M.F.

The drum-armature direct-current dynamo. Fig. 354 is a diagram showing the construction of a commercial two-pole direct-current dynamo of the drum-armature type. At a given instant currents are being induced in the same direction in all the conductors on the left half of the armature. The cross on each of these conductors, representing the tail of a retreating arrow, is to indicate that while the armature is being forced to rotate counterclockwise these currents flow away from the reader. No E.M.F.'s are induced in the conductors at the top and bottom of the armature, where the motion is parallel to the magnetic lines. On the right half of the ring, on the other hand, the induced currents are all in the opposite direction, that is, toward the reader, since the conductors are here all being forced to move up instead of

down. The dot in the middle of each of these conductors represents the head of an approaching arrow. It will be seen, however, in tracing out the connections, 1, 1_1, 2, 2_1, 3, 3_1, etc. of Fig. 354 (the dotted lines representing connections at the back of the drum), that the coil is so wound about the drum that the currents in both halves are always flowing toward one brush *b*, from which they are led to the external circuit and back at *b′*. This condition always exists, no matter how fast the rotation; for it will be seen that as each loop rotates into the position where the direction of its current reverses, it passes a brush and therefore at once becomes a part of the circuit on the other half of the drum, where the currents are all flowing in the opposite direction. Fig. 355 shows a four-pole generator, and in Fig. 357 may be seen more clearly the drum-wound armature. Fig. 366 (p. 416) illustrates the method of winding such an armature, each coil beginning on one segment of the commutator and ending on the segment next it.

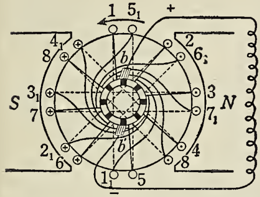


FIG. 354. The direct-current dynamo, drum winding

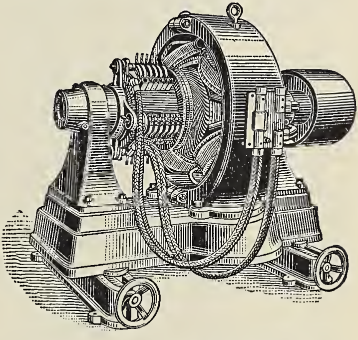


FIG. 355. A four-pole direct-current generator

Excitation of the field. In some of the earlier dynamos the field was produced by permanent magnets. Such dynamos, called magnetos, were used on early automobiles. It is much cheaper and more satisfactory, however, to use electromagnets. In some cases the current for these electromagnets is

furnished from a separate source; but most direct-current dynamos are now of the self-exciting type, that is, the current for exciting the field is taken from the dynamo circuit itself. There are three kinds of dynamos: (1) The series-wound dynamo has the field circuit in series with the external circuit. Thus, when the external current increases, the current exciting the field increases and the E.M.F. of the dynamo rises. (2) The shunt-wound dynamo has its field in parallel with the load circuit. Hence, when the external load increases, the current through the field magnets decreases, thus decreasing the E.M.F. of the dynamo. (3) The compound-wound dynamo has both series and shunt field windings. By combining these two, it is possible to have a fairly constant E.M.F. over a great range of loads. For this reason compound-wound dynamos are used on almost all long-line circuits, the load being connected in parallel, as in Fig. 356.

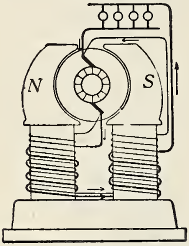
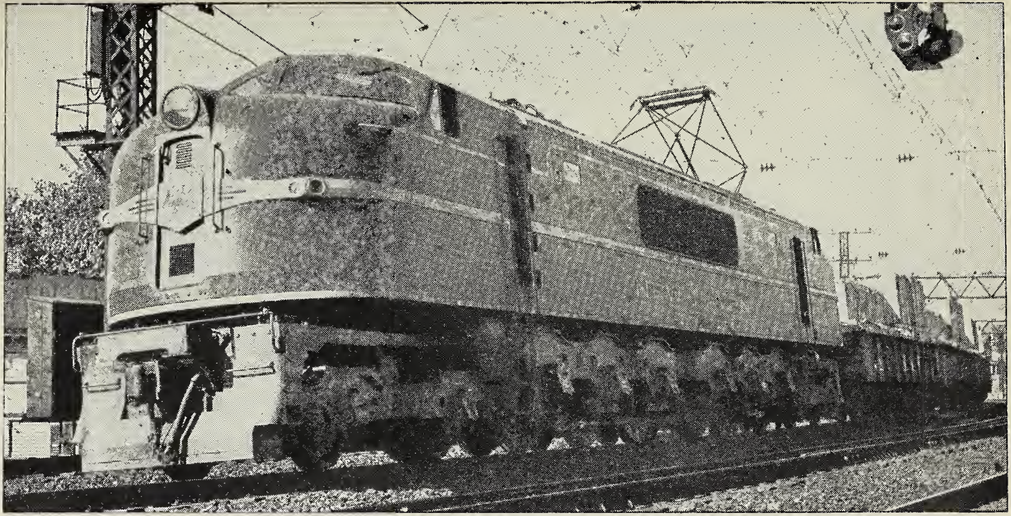


FIG. 356. The compound-wound dynamo

In all self-exciting machines there is enough residual magnetism left in the iron cores after stopping to start feeble induced currents when the machine is started up again. These currents immediately increase the strength of the magnetic field, and so the machine builds up its current until the iron of the field magnets is brought to a state of saturation. (See opposite page 374 for a small lighting plant.)

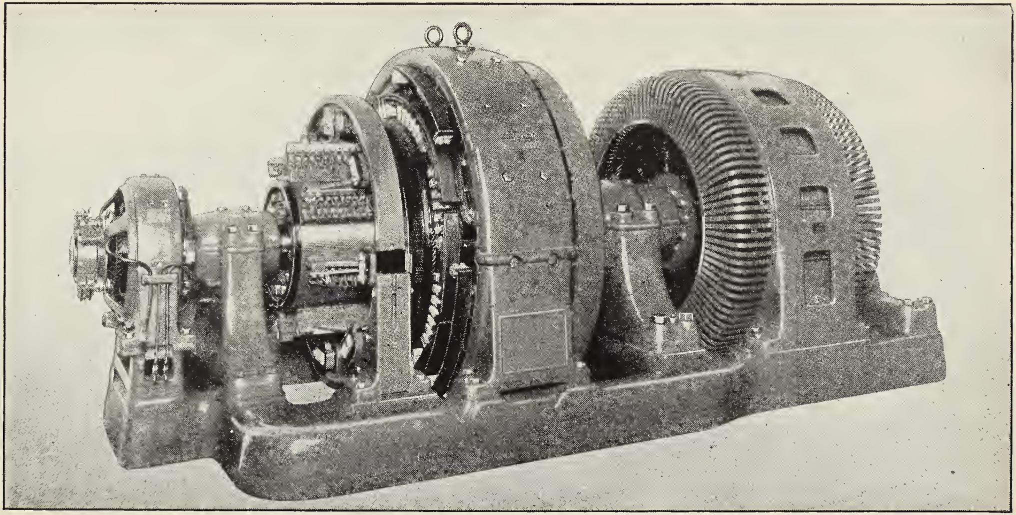
The electric motor. In construction the electric motor differs in no essential respect from the dynamo. The difference is merely in the direction in which the energy is transformed. In the dynamo it is from mechanical to electrical; in the motor, the reverse. It will be found that in general a dynamo can be made to run as a motor, and vice versa. To analyze the operation as a motor of such a machine as that shown in Fig. 352, suppose a current from an outside source is first sent



Electric Locomotive

Electric locomotives are increasingly used not only for passenger service but for rapid and heavy freight service. Such locomotives are generally provided with a number of motors and can pull a heavy train at sixty miles an hour.

The giant locomotive pictured has a capacity of 5000 horsepower. Power is obtained from trolley, pantograph (as above), or third rail. (Courtesy of News Bureau, General Electric Company)



A Motor-Generator Set

This motor-generator set consists of an alternating-current motor (seen at the right end), which may be operated on 2300 or 4000 volts. It drives the 8-pole generator (see center), to which it is directly connected. The generator delivers direct current at 600 volts. It has a drum-wound armature, and its field is excited by a direct current from a 4-pole, 125-volt exciter mounted on the extreme left end of the shaft. Motor-generator sets similar to this one are used to furnish direct current from an alternating-current source to operate electric shovels (see opposite page 156)

around the coils of the field magnets and then into the armature at b'. Here it will divide and flow through all the conductors on the left half of the ring in one direction, and through all those on the right half in the opposite direction. Hence, in accordance with the motor rule, all the conductors on the left side are urged upward by the influence of the field, and all those on the right side are urged downward. The armature will therefore begin to rotate clockwise, and this rotation will continue as long as the current is sent in at b' and out at b; for as fast as coils pass either b or b', the direction of the current flowing through them changes, and therefore the direction of the force acting on them changes. The commutator keeps these conditions always fulfilled. The left half is therefore always urged up and the right half down. The greater the strength of the current, the greater the force acting to produce rotation.

If the armature is of the drum type (Fig. 354), the conditions are not essentially different; for, as may be seen by following out the windings, the current entering at b' will flow through all the conductors on the left half in one direction and through those on the right half in the opposite direction. (The *induction* motor is pictured and described opposite page 393 and also on page 431.)

[Direct-current motors. Motors are of three types, *shunt-wound*, *series-wound*, and *compound-wound*. Shunt-wound motors are used to run machinery of various kinds, both in factories and in homes. Their speed does not vary appreciably with their load. Series-wound motors are used on vehicles, cranes, and the like where a very high starting torque (turning effect) is required. Electric streetcars are nearly all operated by direct-current series-wound motors placed under the cars and attached by gears to the axles. Fig. 357 shows a typical four-pole streetcar motor. The two upper field poles are raised with the case when the motor is opened for inspection, as in the figure. The current is generally supplied by compound-wound dynamos which maintain a constant potential of about 550 volts between the

trolley or third rail and the track, which is used as the return circuit. The cars are always operated in parallel, shown in Fig. 358. In a few instances street cars are operated upon alternating-current, instead of upon direct-current, circuits.

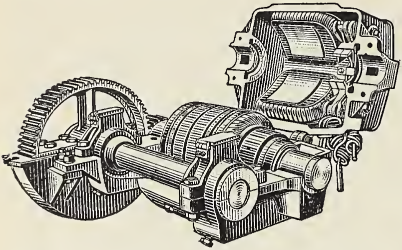


FIG. 357. Railway motor, upper field raised

In such cases the motors are essentially the same as direct-current series-wound motors; for since in such a machine the current must reverse in the field magnets at the same time that it reverses in the armature, it will be seen that the armature is always impelled to rotate in one direction, whether it is supplied with a direct or with an alternating current. Alternating-current motors are not well adapted to starting with full load. Compound-wound motors are used where constant speed is required, as in printing-press installations etc.

FIG. 358. Streetcar circuit

[Series motors of small rating ($\frac{1}{8}$ horsepower or less) are used on both direct and alternating current for running sewing machines, vacuum cleaners, etc. Such motors are called universal motors.

Back E.M.F. in motors. Group from four to six 100-watt lamps in parallel and then connect the group in series with a motor of say $\frac{1}{10}$ horsepower (the familiar 75-watt demonstration school dynamo will serve the purpose, if used as a motor). Attach to the house

circuit. As the speed of rotation of the motor increases, the lamps grow dim. If the motor is now slowed by friction at the pulley wheel, the lamps grow brighter.

We learn, therefore, that the greater the speed of the motor, the less the current passing through it. When an armature is set into rotation by sending a current from some outside source through it, its coils move through a magnetic field as truly as if the rotation were produced by a steam engine, as is the case in running a dynamo. An induced E.M.F. is therefore set up by this rotation. In other words, while the machine is acting as a motor, it is also acting as a dynamo. The direction of the induced E.M.F. due to this dynamo effect will be seen, from Lenz's law or from a consideration of the dynamo and motor rules, to be opposite to the outside P.D., which is causing current to pass through the motor. The faster the motor rotates, the faster the lines of force are cut, and hence the greater the value of this so-called *back E.M.F.* If the motor is doing no work, the speed of rotation will increase until the back E.M.F. reduces the current to a value simply sufficient to overcome friction. It will be seen, therefore, that, in general, the faster the motor goes, the less the current which passes through its armature, for this current is always due to the *difference* between the P.D. applied at the brushes — 550 volts in the case of trolley cars — and the back E.M.F. When the motor is starting, the back E.M.F. is zero; and hence, if the full 550 volts were applied to the brushes, the current sent through would be so large as to ruin the armature through overheating. To prevent this, large motors are furnished with a *starting box*, consisting of resistance coils which are thrown into series with the motor on starting, and thrown out gradually as the speed increases and the back E.M.F. rises.* Trolley cars are usually run by two motors which, on starting, work in series, so that each supplies a part of the starting resistance for the other. After

* This discussion should be followed by a laboratory experiment on the study of a small electric motor or dynamo. See, for example, Experiments 48 and 49 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

speed is acquired, they work in parallel. This is a more economical method than resistance control alone.

The recording watt-hour meter. The recording watt-hour meter (Fig. 359) is the instrument which measures the amount of electricity used. It is essentially an electric motor containing no iron, so that the current through the armature A is proportional to the P.D. between the mains, while the current through the field magnets F is the current flowing into the house. Therefore the force acting between A and F, or the turning power on A (torque), is proportional to the product of volts by amperes; that is, it is proportional to the watts consumed. The recording dials, which are connected to the worm gear G, have therefore a speed which is proportional to the *watts* used, and their total rotation is proportional to the total energy, or *watt-hours*, consumed.

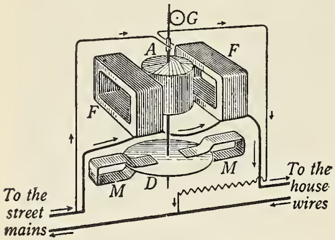


FIG. 359. Interior of a watt-hour meter

The electric clock. The extreme constancy of rotation of the huge modern power-plant dynamo, the alternating currents from which come into nearly every home, has improved home timekeeping. The electric clock is merely a small alternating-current motor run by, and necessarily in synchronism with, the central-station generator.

Summary. A dynamo generates E.M.F. through mutual cutting of conductors and lines of magnetic force. It transforms mechanical energy into electrical energy.

An electric motor is essentially the same in construction as a dynamo. It transforms electrical energy into mechanical work.

The commutator of a dynamo is for the purpose of switching the alternating current in the armature to a direct current in the line.

Back E.M.F. is generated in a motor in accordance with Lenz's law.

A watt-hour meter is constructed to rotate at a speed proportional to the kilowatts, or power, used, and reads kilowatt-hours directly.

QUESTIONS AND PROBLEMS

A

1. (*a*) What are the essential parts of an alternating-current generator? (*b*) Describe its operation. (*c*) Does it create energy? Give a reason for your answer.

2. (*a*) What is the function (use) of the field magnet of a dynamo? (*b*) Wood is cheaper than iron; why are not the field cores made of wood?

3. Explain how an alternating current in the armature is switched into a unidirectional current in the external circuit.

4. What is the essential difference in construction between a direct-current and an alternating-current dynamo?

5. If a current is sent into the armature of Fig. 352 at *b′*, and taken out at *b*, which way will the armature revolve?

6. Why does it take twice as much work to keep a dynamo running when 1000 lights are on the circuit as when only 500 are turned on?

7. Explain why a series-wound motor can run on either a direct or an alternating circuit.

B

1. Will it take more work to rotate a dynamo armature when the circuit is closed than when it is open? Why?

2. Two successive coils on the armature of a multipolar alternator are cutting lines of force which run in opposite directions. How does it happen that the currents generated flow through the wires in the same direction? (Fig. 349.)

3. Explain the process of *building up* in a dynamo.

4. How would it affect the voltage of a dynamo (*a*) to increase the speed of rotation of its armature? Why? (*b*) to increase the number of turns of wire in the armature coils? Why? (*c*) to increase the strength of the magnetic field? Why?

5. When an electric fan is first started, the current through it is much greater than it is after the fan has attained its normal speed. Why?

6. When a wire is cutting lines of force at the rate of 100,000,000 per second, there is induced in it an E.M.F. of 1 volt. A certain dynamo armature has 50 coils of 5 loops each and makes 600 revo

lutions per minute. Each wire cuts 2,000,000 lines of force twice in a revolution. What is the E.M.F. developed?

7. Single dynamos often operate as many as 1000 incandescent lamps at 110 volts. If these lamps are all arranged in parallel and each requires a current of 0.5 ampere, (*a*) what is the total current furnished by the dynamo? (*b*) What is the rating of the machine in kilowatts and in horsepower?

8. How many 110-volt lamps like those of Problem 7 can be lighted by a 100-kilowatt generator?

9. If a series-wound dynamo is running at a constant speed, (*a*) what effect will be produced on the strength of the field magnets by diminishing the external resistance and thus increasing the current? (*b*) What will be the effect on the E.M.F.? (Remember that the whole current goes around the field magnets.) (See page 404.)

10. If a shunt-wound dynamo is run at constant speed, (*a*) what effect will be produced on the strength of the field magnets by reducing the external resistance? (*b*) What effect will this have on the E.M.F.?

11. In an incandescent-lighting system the lamps are connected in parallel across the mains. Every lamp which is turned on, then, diminishes the external resistance. Explain from a consideration of Problems 9 and 10 why a compound-wound dynamo (Fig. 356) keeps the P.D. between the mains constant.

12. A direct-current generator operating at 220 volts furnishes to a factory a current of 50 amperes through a line having a resistance of 0.2 ohms. (*a*) How much power is developed by the generator? (*b*) At what voltage does the factory receive its current?

13. An electric motor developed 2 H.P. when taking 16.5 amperes at 110 volts. Find the efficiency of the motor. (One horsepower = 746 watts.)

14. The resistance of the wire connecting a generator to a motor is .05 ohm; the generator can deliver 200 amperes. (*a*) What is the fall in potential between the generator and the motor? (*b*) How many watts are expended in sending the current through the wire?

15. An electric motor having an efficiency of 85 per cent develops 3 H.P. when connected to a 220-volt circuit. How much current flows through the motor?

16. Name two uses and two disadvantages (*a*) of mechanical friction; (*b*) of electrical resistance.

Principle of the Induction Coil and Transformer

Currents induced by varying the strength of a magnetic field. The principle of the generator, or dynamo, is that an E.M.F. is generated in a conductor cutting lines of force. We should expect the same effect to occur if the conductor remained stationary and the lines of force moved across it. More specifically, we should expect an induced E.M.F. to occur in a coil when a field is created or destroyed near it, thus changing the number of lines of force enclosed by the coil. The following experiment tests this expectation:

Wind about 500 turns of No. 28 insulated copper wire around one end of an iron core, as in Fig. 360, and connect the coil to a galvanometer *G*. Wrap about 500 more turns about another portion of the core and connect the second coil to two dry cells. When the key *K* is closed, the deflection of the galvanometer will indicate that a temporary current has been induced in one direction through the coil *s*; and when it is opened, an equal but opposite deflection will indicate an equal current flowing in the opposite direction.

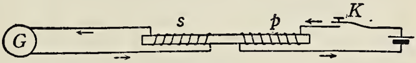


FIG. 360. Induction of current by magnetizing and demagnetizing an iron core

The experiment illustrates the principle of the induction coil and the transformer. The coil *p*, which is connected to the source of the current, is called the *primary coil*, and the coil *s*, in which the currents are induced, is called the *secondary coil*. Causing lines of force to spring into existence inside of *s* (in other words, magnetizing the space inside of *s*) has caused an induced current to flow in *s*; and demagnetizing the space inside of *s* has also induced a current in *s* in accordance with the general principle stated on page 393, that *any change in the number of magnetic lines of force which thread through a coil induces a current in the coil.* We may think of the lines as always existing as closed loops (see Fig. 291) which collapse upon demagnetization to mere double lines (which cancel each other) at the axis of the coil. Upon mag-

netization one of these two lines springs out, cutting the encircling conductors and inducing a current.

Direction of the induced current. Lenz's law, which, it will be remembered, followed from the principle of conservation of energy, enables us to predict at once the direction of the induced currents in the above experiments; and an observation of the deflections of the galvanometer enables us to show that our predictions are correct. Consider first the case in which the primary circuit is *made* and the core thus magnetized. According to Lenz's law the current induced in the secondary circuit must be in such a direction as to *oppose the change* which is being produced by the primary current, that is, in such a direction as to tend to magnetize the core oppositely to the direction in which it is being magnetized by the primary. This means, of course, that the induced current in the secondary must encircle the core in a direction *opposite* to the direction in which the primary current encircles it. We learn, therefore, that *on making the current in the primary the current induced in the secondary is opposite in direction to that in the primary.*

When the current in the primary is *broken*, the magnetic field created by the primary tends to die out. Hence, by Lenz's law, the current induced in the secondary must be in such a direction as to tend to oppose this process of demagnetization, that is, in such a direction as to magnetize the core in the *same* direction in which it is magnetized by the decaying current in the primary. Therefore *at break the current induced in the secondary is in the same direction as that in the primary.*

E.M.F. of the secondary. If half of the 500 turns of the secondary *s* (Fig. 360) are unwrapped, the deflection will be found to be just half as great as before. Since the resistance of the circuit has not been changed, we learn from this that *the E.M.F. of the secondary is proportional to the number of turns of wire upon it* — a result which followed also from page 395. If, then, we wish a high E.M.F. in the secondary, we make it of a very large number of turns of fine wire.

Self-induction. If, in the experiment illustrated in Fig. 360, the coil *s* had been made a part of the same circuit as *p*, the E.M.F.'s induced in it by the changes in the magnetism of the core would of course have been just the same as above. In other words, when a current starts in a coil, the magnetic field which it itself produces tends to induce a current opposition in direction to that of the starting current, that is, tends to oppose the starting of the current; and when a current in a coil stops, the collapse of its own magnetic field tends to induce a current in the same direction as that of the stopping current, that is, tends to oppose the stopping of the current. This means merely that *a current in a coil acts as though it had inertia, and opposes any attempt to start or stop it.* This inertialike effect of a coil upon itself is called *self-induction.*

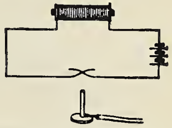


FIG. 361. Spark from self-induction

Place a few dry cells in a circuit containing a coil of a large number of turns of wire wound upon iron (Fig. 361), the circuit being closed at some point by touching two bare copper wires together. Holding the bare wire in the fingers, break the circuit between the hands and observe the shock caused by the current which the E.M.F. of self-induction sends through your body. Without the coil in circuit you will obtain no such shock, though the current stopped when you break the circuit will be many times larger. Break the circuit in gas escaping from a jet; the gas will be ignited. This is the principle of electric gas-lighting systems.

The induction coil. The induction coil, as usually made (Fig. 362), consists of a soft-iron core *C* composed of a bundle of soft-iron wires; a primary coil *p* wrapped around this core and consisting of say 200 turns of coarse copper wire (for example, No. 16), which is connected into the circuit of a battery through the contact point at the end of the screw *d*; a secondary coil *s* surrounding the primary in the manner indicated in the diagram and consisting generally of between 30,000 and 1,000,000 turns of No. 36 copper wire, the terminals of which are the points *t* and *t′*; and a hammer *b* or other

automatic arrangement for making and breaking the circuit of the primary. (See the ignition system diagramed in Fig. 363.)

Hold the hammer b away from the opposite contact point by means of the finger, then touch it to this point and pull it quickly away. *A spark will be found to pass between t and t' at break only — never at make.* This is because, on account of the opposing influence at *make* of self-induction in the primary, the magnetic field about the primary rises very gradually to its full strength, and hence its lines pass into the secondary coil comparatively slowly. At *break*, however, by separating the contact points very quickly we can make the current in the primary fall to zero in an exceedingly short time, perhaps not more than .00001 second; that is, we can make all its lines pass out of the coil in this time. Hence the *rate* at which lines

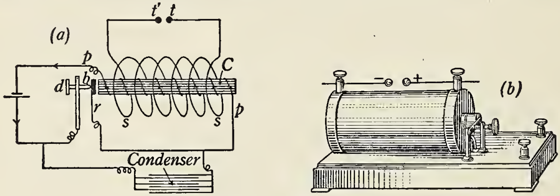


FIG. 362. Induction coil

thread through or cut the secondary is perhaps 10,000 times as great at break as at make, and therefore the E.M.F. is also something like 10,000 times as great. In the normal use of the coil the circuit of the primary is automatically made and broken at b by means of the magnet and the spring r, precisely as in the case of the electric bell. Let the student analyze this part of the coil for himself. The condenser shown in the diagram, with its two sets of plates connected to the conductors on either side of the spark gap between r and d, is not an essential part of a coil, but when it is introduced it is found that the length of the spark which can be sent across between t and t' is considerably increased. The reason is as follows: When the circuit is broken at b, the inertia (that is, the self-induction) of the primary current tends to make a spark jump across from d to b; and if this happens, the current continues to flow through this spark (or arc) until the terminals have become separated through a considerable distance. This makes the current die down gradually instead of suddenly, as it ought to do to produce a high E.M.F.; but when

a condenser is inserted, as soon as *b* begins to leave *d* the current begins to flow into the condenser, and this gives the hammer time to get so far away from *d* that an arc cannot be formed. This means a sudden break and a high E.M.F. Since a spark passes between *t* and *t'* only at break, it must always pass in the same direction. Coils which give 24-inch sparks (perhaps 500,000 volts) are not uncommon. Such coils usually have hundreds of miles of wire upon their secondaries.

[Induction coils are used in the ignition systems of all modern automobiles (Fig. 363) to produce sparks in the

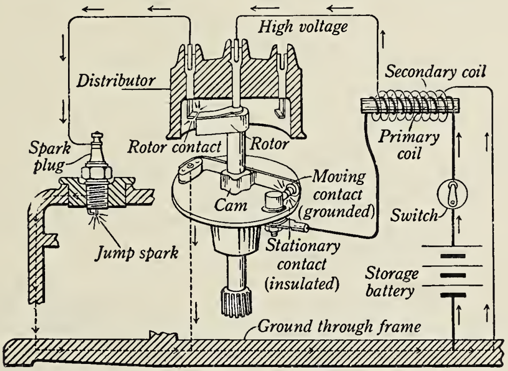


FIG. 363. Automobile ignition system

cylinders and thus to ignite the gasoline. A contact cam geared to the engine makes and breaks the current in the primary at the proper times, and a distributor, also geared to the engine, sends the current in the secondary to the proper spark plug.

[**Laminated cores; Foucault currents.** The core of an induction coil should always be made of a bundle of soft-iron wires insulated from one another by means of shellac or varnish (see Fig. 364); for whenever a current is started or stopped in the primary *p* of a coil furnished with a *solid* iron core (see Fig. 365), the change in the magnetic field of the primary in-

duces a current in the conducting core *C*, for the same reason that it induces one in the secondary *s*. This current flows around the body of the core in the same direction as the induced current in the secondary that is, in the direction of the arrows. The only effect of these so-called *eddy*, or *Foucault*, currents is to heat the core. This is obviously a waste of energy. If we can prevent the appearance of these currents, all the energy which they would waste in heating the core may be made to appear in the current of the secondary. The core is therefore built of varnished iron wires which run parallel to the axis of the coil, that is to say, perpendicular to the direction in which the currents would be induced. The induced E.M.F. therefore finds no closed circuits in which to set up a current (Fig. 364). It is for the same reason that the iron cores of dynamo and motor armatures,

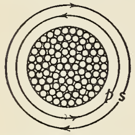


FIG. 364. Core of insulated iron wire

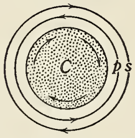


FIG. 365. Diagram showing eddy currents in solid core

instead of being solid, consist of iron disks placed side by side, as shown in Fig. 366, and insulated from one another by films of oxide. A core of this kind is called a *laminated* core. It will be seen that in all such cores the spaces, or slots, between the laminae must run *at right angles to the direction of the induced E.M.F.*, that is, perpendicular to the conductors upon the core.

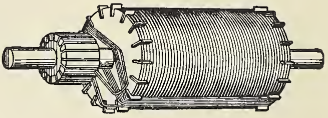


FIG. 366. Laminated drum-armature core with commutator, showing one coil wound on the core

The transformer. The chief difference between an induction coil and a transformer is that in the latter the core *R* (Fig. 367), instead of being straight, is bent into the form of a ring or is given some other shape such that the magnetic lines of force have a continuous iron path instead of being

obliged to push out into the air, as in the induction coil. Furthermore, it is always an alternating instead of an intermittent current which is sent through the primary *A*. Sending such a current through *A* is equivalent to first magnetizing the core in one direction, then demagnetizing it, then magnetizing it in the opposite direction, etc. The magnetic field is set up and destroyed with every alternation, causing a continuous *flux* of magnetic lines of force through the secondary coil. An alternating current is thus set up in the secondary. The result of these changes in the magnetism of the core is of course an induced alternating current within the secondary coil *B*.

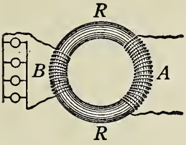


FIG. 367. Diagram of transformer

The use of the transformer. The use of the transformer is to convert an alternating current from one voltage to another which, for some reason, is found to be more suitable. In electric lighting, for example, where an alternating current is used, the E.M.F. generated by the dynamo is usually 2200 volts, a voltage too high to be introduced safely into private houses. Hence transformers are connected across the main conductors in the manner shown in Fig. 368 to reduce the voltage to 110 or 220. The current which passes into the houses to supply the lamps does not come directly from the dynamo. It is an induced current produced in the transformer.

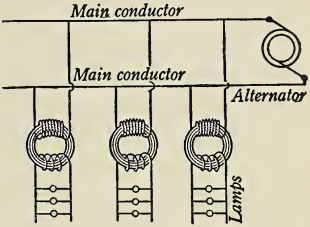


FIG. 368. Alternating-current lighting circuit with transformers

Through the use of small transformers the voltage of the current of the house-lighting circuit is further reduced and made available for the ringing of doorbells and for other purposes requiring voltages different from that on the mains.

Pressure in primary and secondary. If there are a few turns in the primary and a large number in the secondary, the transformer is called a *step-up* transformer, because the P.D. produced at the terminals of the secondary is greater than that applied at the terminals of the primary. In electric lighting, transformers are mostly of the *step-down* type; that is, a high P.D. (say 2200 volts) is applied at the terminal of the primary, and a lower P.D. (say 110 volts) is obtained at the terminals of the secondary. In such a transformer the primary will have twenty times as many turns as the secondary. In general, *the ratio between the voltages at the terminals of the primary and secondary is the ratio of the number of turns of wire upon the two.*

Efficiency of the transformer. In a perfect transformer the efficiency would be unity. This means that the electric power, or watts, put into the primary (that is, the volts applied to its terminals times the amperes flowing through it) would be exactly equal to the power, or watts, taken out in the secondary (that is, the volts generated in it times the strength of the induced current); and, in fact, in actual transformers the latter product is often more than 97 per cent of the former (that is, there is less than 3 per cent loss of energy in the transformation). This lost energy appears as heat in the transformer. This transfer which goes on in a big transformer of huge quantities of power from one circuit to another entirely independent circuit, without noise or motion of any sort and almost without loss, is one of the most wonderful phenomena of modern industrial life.

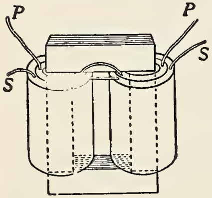


Fig. 369. The core type of transformer

[**Commercial transformers.** Fig. 369 illustrates a common type of transformer used in electric lighting. The core is built up of sheet-iron laminae about $\frac{1}{2}$ millimeter thick. Fig. 370 shows a section of the same transformer. The closed magnetic circuit of the core is indicated by the dotted lines. The prima-

ries and the secondaries are indicated by the letters P and S. Fig. 371 is the case in which the transformer is placed. Such cases may be seen attached to poles outside houses wherever alternating currents are used for electric lighting (Fig. 372).

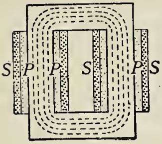


FIG. 370. Cross section of transformer, showing shape of magnetic field

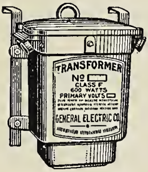


FIG. 371. Transformer case

Electrical transmission of power. Since the rate of production of electrical energy by a dynamo is the product of the E.M.F. generated by the current furnished, it is evident that in order to transmit from one point to another a given number of watts, say 10,000, it is possible to have either an E.M.F. of 100 volts and a current of 100 amperes or an E.M.F. of 1000 volts and a current of 10 amperes. As we have seen, the heating effects of a current depend on the resistance and the square of the current. Since in transmission energy expended in heat is wasted energy, it is desirable to have as low a current as is practicable. In the example above, the energy lost in heat in the 10-ampere current will be $\frac{1}{100}$ as much as in the case of the 100-ampere current, though the same amount of energy is transmitted in both cases. Hence for long-distance transmission, where line losses are considerable, it is important to use the highest possible voltages, limited only by insulation problems.

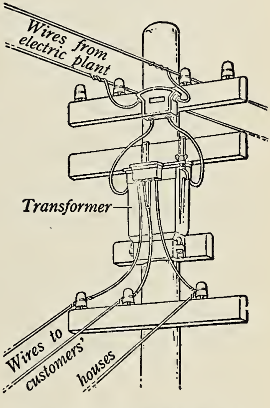


FIG. 372. Transformer on electric-light pole

The large 87,000-horsepower alternating-current dynamos on the American side of Niagara Falls generate directly

12,000 volts. This is the highest voltage thus far produced by generators. In all cases where these high pressures are employed, they are transformed down at the receiving end of the line to a safe and convenient voltage (from 50 to 550 volts) by means of *step-down* transformers.

It will be seen from the facts given above that alternating currents are best suited for long-distance transmission. The Big Creek plant in California transmits power 241 miles at a pressure of 220,000 volts. (See opposite page 187.) The Southern Sierras Power Company sends current 830 miles across the desert. In all such cases *step-up* transformers, situated at the powerhouse, transfer the electrical energy

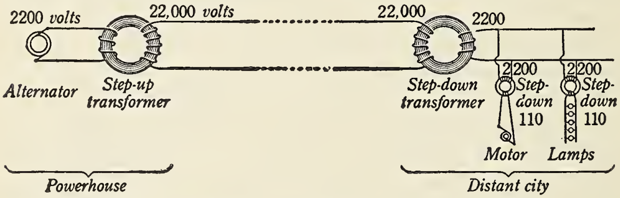


FIG. 373. High-voltage long-distance transmission line

developed by the generator to the line, and *step-down* transformers, situated at the receiving end, transfer it to the motors or lamps which are to be supplied (Fig. 373). (See opposite pages 186 and 348 for hydroelectric plants in which dynamos are run by water wheels.)

Changing alternating current to direct current. The alternating current furnished by most modern power plants is not suitable for some purposes, such as charging batteries and running streetcar motors or depositing copper or other metals from solution. There are various methods of *rectifying* an alternating current, or, in other words, of changing it to a direct current. The simplest is the motor generator, which consists simply of an alternating-current motor that drives a direct-current generator. A similar device used on some streetcar circuits is the rotary converter. This runs as a

motor, taking the alternating current into the armature by means of slip rings at one end of the shaft and giving out direct current through a commutator at the other end.

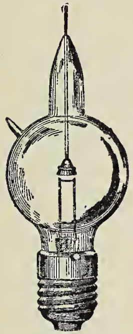


FIG. 374. Tungar bulb

[The most convenient device for charging storage batteries is the tungar rectifier. Its principles are as follows. Negative electrons are found to escape from a filament that is heated to incandescence; and if this filament is then made more than say 25 volts negative with respect to a neighboring anode, any gas that surrounds the filament is found to be ionized (split into positively and negatively charged parts) by the violence of the blows which the electrons strike against its molecules. It is thus made conducting. The bulb (Fig. 374) is filled with argon to a pressure of 3 to 8 centimeters. The anode is a small cone of graphite or tungsten, and the cathode is a coiled tungsten filament. When the rectifier is in operation, the cone and the filament are alternately + and −, one being + while the other is −. When the cone is + and the filament −, the negative electrons from the filament are forced across the space from the filament to the cone, and the argon, which is thereby ionized, carries the current from the cone to the filament. When the cone is − and the filament +, the negative electrons cannot escape from the filament; hence the gas does not become conducting. The principle of operation can be understood from Fig. 375.

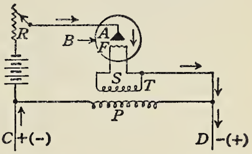


FIG. 375. Principle of operation of the tungar rectifier

[The rectifier is connected to the alternating-current line at C and D. The alternating current in the primary coil P of the transformer T causes an induced current in S, which keeps the filament F incandescent. Under the action of the current, A and F are alternately + and −. When F is −,

the electrons escape and ionize the gas, permitting the current to pass. When F is $+$ the negative electrons are driven back into the filament and cannot escape to ionize the gas. Hence no current passes. In this way a unidirectional pulsating current passes through the storage batteries or other load.

Principle of the carbon microphone. Arrange a dry cell, an ammeter, and two pieces of electric-arc carbon in series (Fig. 376). Press the carbons *very gently* and observe the reading of the ammeter. Press gradually harder, then gradually less, watching the instrument. The current increases with increase in pressure, and decreases with decrease in pressure.

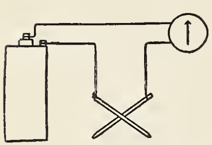


FIG. 376. The principle of the carbon transmitter

This peculiar behavior of carbon in offering a variable resistance with variation in pressure is taken advantage of in constructing the carbon transmitter of the telephone. In the modern transmitter, however, the current is made to traverse many particles of granular carbon, which, lying loosely together, furnish a very great number of loose contacts (Fig. 379).

Principle of the telephone. The telephone was invented in 1875 by Alexander Graham Bell of Washington and Elisha

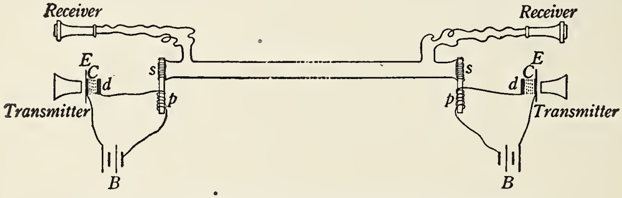
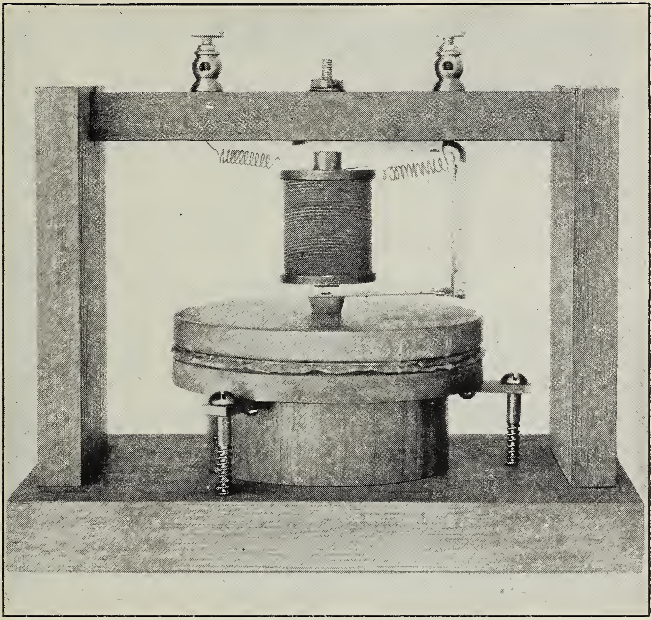


FIG. 377. The telephone circuit (local-battery system)

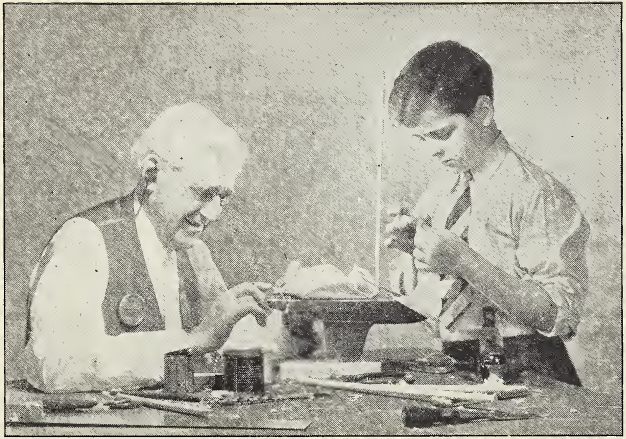
Gray of Chicago. The simple local-battery system shown in Fig. 377 is used largely on rural telephone lines.

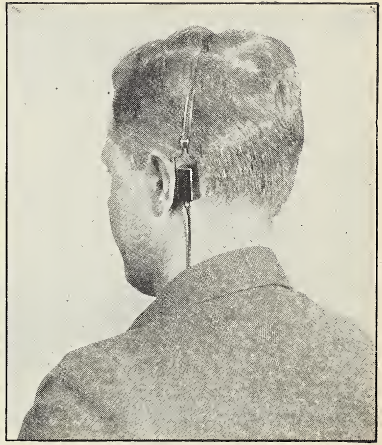
The current from the battery B is led first to the back of the diaphragm E, whence it passes through a little chamber C, filled with granular carbon, to the conducting back d of the



Model of Bell's First Telephone

This model is a duplicate of the instrument through which speech sounds were first transmitted electrically in 1875. The vibrations of the diaphragm as it responds to surrounding sounds carry with them the little spring-held armature and thus induce correspondingly fluctuating currents in the coil. These can be carried from the binding posts to any desired point





Aids to the Deaf: the Audiphone; the Bone-Conduction Set

Through use of a device which is essentially a very small but highly sensitive telephone system, science has rendered inestimable aid to those having impaired hearing. The picture at the left shows fastened to a pocket the small device (a carbon microphone) which receives the sound. Attached to the ear is the tiny receiver. A two-stage vacuum-tube amplifier with batteries (not here shown) is used to intensify without distortion the microphone impulses. The picture at the right shows a bone-conduction receiver, which is like the audiphone save that the outer ear is here not used at all, the sound waves going directly through the bone to the nerves of the inner ear. The great efficiency of this receiver is largely due to "Permalloy." (Courtesy of the Bell Telephone Laboratories)

transmitter, and thence through the primary coil *p* of the transformer, and then back to the battery *B*.

When a sound is made in front of the mouthpiece, the vibrations produced by the sounding body are transmitted by the air to the diaphragm, thus causing the latter to vibrate back and forth. These vibrations of the diaphragm vary the pressure upon the many contact points of the granular carbon through which the primary current flows. This produces considerable variation in the resistance of the primary circuit, so that as the diaphragm moves forward, that is, toward the carbon, a comparatively large current flows through *p*, and as it moves back, a much smaller current. These changes in the current strength in the primary *p* produce changes in the magnetic field of the soft-iron core of the transformer. Currents are thus induced in the secondary *s* of the transformer, and these currents pass over the line and affect the receiver at the other end. A step-up transformer is used to get sufficient potential to work through the high resistance of a long line.

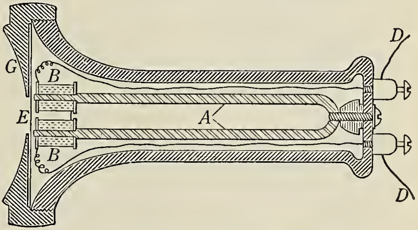


FIG. 378. The modern receiver

A modern telephone receiver is shown in Fig. 378. It consists of a permanently magnetized U-shaped piece of steel in front of whose poles is a soft-iron diaphragm which *almost* touches the ends of the magnet. Wound in opposite directions upon the two poles are coils of fine insulated wire in series with each other and the line wire. *G* is the earpiece, *E* the diaphragm, *A* the U-shaped magnet, and *B* the coils, consisting of many turns of fine wire and having soft-iron cores. When the rapidly alternating current from the secondary coil *s* (Fig. 377) flows through the coils of the receiver, the poles of the permanent magnet are thereby alternately

strengthened and weakened in synchronism with the sound waves falling upon the diaphragm of the transmitter. The variations in the magnetic pull upon the diaphragm of the receiver cause it to send out sound waves exactly like those which fell upon the diaphragm of the transmitter.

Telephonic conversation can be carried on over great distances as rapidly as if the parties sat on opposite sides of the same table. An electrical impulse passes over the telephone wires from New York to San Francisco in about one fifteenth of a second. The use of distortionless vacuum-tube repeaters makes possible such long-distance transmission of speech. There are 17,500,000 telephones in use in the United States and 87,000,000 miles of telephone wire. The New York-Chicago telephone cable, constructed at a cost of $25,000,000, is 861 miles long, $2\frac{5}{8}$ inches in diameter, and contains 447,000 miles of wire. It can carry 250 telephone messages and, simultaneously with them, 500 telegraph messages. The cross section of a complete long-distance transmitter is shown in Fig. 379. The current goes through granular carbon held between solid blocks of carbon.

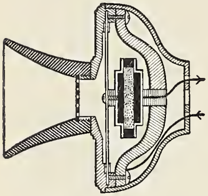


Fig. 379. Cross section of a long-distance telephone transmitter

Summary. While the primary current is increasing, the induced current in the secondary flows opposite to it. While the primary current is decreasing, the induced current flows in the same direction.

Self-induction is the occurrence of an induced E.M.F. in a part of the same circuit in which the original current flows, and, in accord with Lenz's law, it makes the current appear to have inertia.

The ratio of the voltages in the primary and secondary coils of a transformer is equal to the ratio of their respective numbers of turns.

In long-distance transmission, heat losses in the line are minimized by using high voltage and low amperage.

Vacuum-tube rectifiers depend for their action upon electron emission by incandescent bodies.

The microphone depends for its action upon the variable resistance of carbon under changing pressure.

In a telephone receiver the poles of a permanent magnet are alternately strengthened and weakened, but not reversed in polarity.

QUESTIONS AND PROBLEMS

A

1. Draw a diagram of an induction coil and explain its action.

2. Explain why an induction coil is able to produce such an enormous E.M.F.

3. Represent by a diagram a step-up transformer, and label the essential parts.

4. What relation must exist between the number of turns on the primary and secondary of a transformer which feeds 110-volt lamps from a main line whose conductors are at 1100 volts P.D.?

5. Make a diagram to show how in the electric-doorbell transformer the 104-volt house current is transformed to an 8-volt current to ring the bell.

6. Suppose 5,000,000 watts of electrical power are to be transmitted a great distance. Which is the more economical way to transmit it, as 50 amperes at 100,000 volts or as 5000 amperes at 1000 volts? Give a reason for your answer.

7. Give as many ways as you can think of for producing an induced E.M.F.

8. Does the spark of an induction coil occur at make or at break? Why?

B

1. A transformer is desired to step down from 220 to 5 volts, and is wound with 1100 turns in the primary coil. How many turns should be put in the secondary coil?

2. A current of 3 amperes at 1000 volts is sent through the primary coil of a transformer having an efficiency of 97 per cent. How many 40-watt lamps can be lighted when connected to the secondary coil of the transformer?

3. Why does a tungar rectifier rectify an alternating current?

4. (*a*) In telephoning from New York to San Francisco how far do you think the sound goes? (*b*) What passes along the telephone wire?

5. Diagram a simple telephone similar to that of Fig. 377 in which are shown only those parts that are necessary to enable one party to speak to the other, no reply from the second party being possible.

6. Make from memory a careful sketch of a telephone transmitter and a receiver, including battery and connections, and explain the action of each instrument.

7. Name three modern electric instruments or machines which have resulted from Oersted's discovery and three that have resulted from Faraday's.

8. A transformer is so wound as to step the voltage of the lighting circuit from 2200 volts down to 110. (*a*) Sketch the transformer and its connections, marking the primary and the secondary, and state the relative number of turns in each. (*b*) If the house circuit uses 40 amperes, what current must flow in the primary?

Characteristics of Alternating-Current Circuits

Impedance. Alternating currents are now used very much more extensively than are direct currents, and for that reason it is important for everyone to understand some of the peculiar characteristics of alternating-current circuits. The following experiment illustrates one of the most striking of these alternating-current effects. If a lamp and a coil, each having a resistance of say 110 ohms, are connected in series, as in Fig. 380, and inserted in a 110-volt direct-current circuit by throwing the double-throw switch to the left, the lamp will glow at a constant brightness, quite independently of whether an iron core is thrust through the coil or removed from it. The ammeter *A* (which should be one that works on either alternating current or direct current) will read the current given by Ohm's law, namely, volts/ohms = 110/220 = 0.5 ampere. But if the experiment is repeated when the switch is thrown into contact with the alternating-

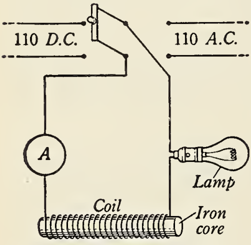


FIG. 380. The choke coil

current terminals, the insertion of the iron core will cause the lamp to grow very dim, and the current will be reduced from about 0.5 ampere to perhaps a tenth of that or even less, depending upon the number of turns of copper wire in the coil.

This experiment shows that Ohm's law, as we have thus far used it, does not work at all on alternating-current circuits possessing appreciable *inductance*. The remarkable choking down of the alternating current is of course due to the self-induction of the coil with its iron core. This sets up an opposing E.M.F., or back voltage, whenever the current is trying to change. In a word, in a direct-current circuit there is nothing to hold back the current except the ohmic resistance between the points to which the potential difference is applied; but in an alternating-current circuit there is something in addition to ohmic resistance. This combined resistance to the flow of alternating current is called *impedance*. The impedance is measured in *equivalent ohms*, often called simply ohms. If in the experiment above the "choked-down current" was found to be .05 ampere, then the impedance was $110/.05 = 2200$ ohms.

This property of inductance in alternating-current circuits makes it possible to adjust the current in any circuit of given voltage by inserting coils of high inductance into the circuit. Such coils are called choke coils. They often prevent nearly all current from passing, even though their resistance may be low.

[**Power factor.** We found on page 382 that in a direct-current circuit the power in watts is the product of volts and amperes. This is also true in a noninductive alternating-current circuit like that of a filament lamp. If, however, we measure with a wattmeter the power in an alternating-current circuit possessing considerable inductance, we find that it falls short of the product of volts and amperes.

[The explanation is simple. In an alternating-current circuit neither E.M.F. nor current is constant. Both build up to a maximum in one direction, fall back to zero, then build up to a maximum in the other direction, as shown in Fig. 381,

and so on. The E.M.F. and the current which one measures are a sort of average of these fluctuations. Now in an inductive circuit we have seen (p. 413) that the self-induction acts to prevent an increase in voltage from resulting immediately in a proportional increase in current. The current acts as if it had inertia. This means that it takes time for the current to build up, or that the increase in current comes a little after the increase in voltage, and the same holds for the decrease. Thus the fluctuations of current are, so to speak, out of step, or "out of phase," with the fluctuations of E.M.F., as in Fig. 381. This phenomenon is known as *lag*, and its magnitude depends on the amount of the inductance.

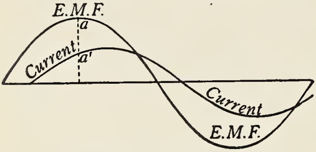


FIG. 381. Lag curves

[It is, then, clear (Fig. 381) that when the E.M.F. is at a maximum, as at a, the current may be quite small, as at a', and vice versa. Thus the product of current and voltage *at a given moment* will be below the product of the average values of the two quantities.

[The fraction by which it is necessary to multiply the product of mean volts and mean amperes (the apparent power) to get the true power is known as the *power factor*. That is,

$$\text{True power (watts)} = \text{volts} \times \text{amperes} \times \text{power factor}.$$

Though this power factor varies with the inductance, in most commercial circuits it runs between 80 per cent and 90 per cent.

[**Condensers in alternating-current circuits.** Connect a lamp and condenser in series and apply a direct current by throwing the switch (Fig. 382) to the left. The lamp does not, of course, light, since the circuit is broken. Now throw the switch over to the alternating-current circuit. The lamp glows.

[This rather surprising effect is very easily explained. A condenser is essentially a reservoir in which a certain amount

of electricity can be stored. When the circuit is put on direct current, the reservoir fills up quickly, and then the current stops. When the circuit is on alternating current, however, the reservoir fills and empties each time the current is reversed, thus permitting an alternating current to flow through the lamp.

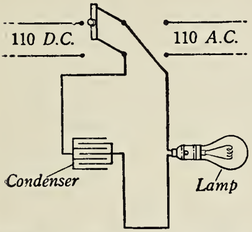


FIG. 382. Effect of a condenser on alternating current

[This property of alternating current is used in the telephone bell. The bell, in series with a condenser, is hooked up in parallel with the receiver (Fig. 383). The bell rings when an alternating current is sent over the wire, but does not respond to the direct current used for voice transmission. Currents of this sort play a very large role in radio.

[**Three-phase alternating currents.** For simplicity we have confined our attention thus far to single-phase alternating currents, such as the one represented by the simple curve of Fig. 348. With an armature winding like that shown in Fig. 349 only such a single-phase alternating current would be produced.

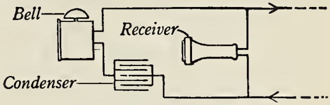


FIG. 383. Telephone bell

[We might, however, have had say three coils for each pole of the field instead of but one. Indeed, it is found possible to weave more copper conducting wires into the slots on the armature — so that a larger fraction of the total wire used is all the time in the intense magnetic field just opposite the pole — if two or three independent circuits are used instead of one. The ends of each of these sets of coils may then be attached to a separate pair of rings, thus providing three quite independent external currents. The phases of these three currents would then be a third of a cycle, or 120°, apart, so that the three currents in this phase system would be represented by Fig. 384.

Having three independent circuits calls for three outgoing and three returning conductors in the external circuit. But it is found possible to connect the outgoing conductors in such a way that each of them serves as the return for the other two circuits. Most large power installations use this three-phase system, all the currents in the external circuit being carried by three conductors. Single-phase currents, such as those used in practically all homes, can be obtained by tapping off currents from any two of these three wires.

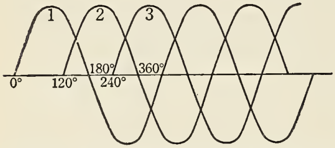


FIG. 384. Curves of alternating currents in a three-phase system

Rotating magnetic fields. A rotating magnetic field is essential for the operation of the induction motor, one of the commonest and simplest types of large-power alternating-current motors. The method of producing a rotating magnetic field is most easily understood by considering a two-phase system such as the one that would be produced by having two instead of three sets of coils to each pole of the generator. The coils are so placed that the currents (Fig. 385) are 90° out of phase (compare with Fig. 384). Suppose these two currents in *Line* 1 and *Line* 2 are conducted through the windings of magnet poles, as shown in Fig. 386. It will be seen from Fig. 385 that when the current in *Line* 1 is a maximum, that in *Line* 2 is zero, so that the magnetic field is as shown in Fig. 386 (*a*). After an eighth of a cycle, or 45° (Fig. 385), the currents in *Line 1* and *Line 2* are equal, and the magnetic field is then as shown in Fig. 386 (*b*). After another 45° the situation is as shown in Fig. 386 (*c*).

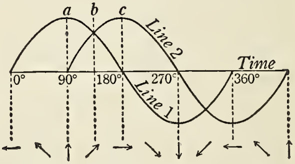


FIG. 385. Curves of two alternating currents which differ in phase by 90°, with arrows showing magnetic field

[There is then set up in the device shown in Fig. 386 a rotating field which would cause a magnet in the field to

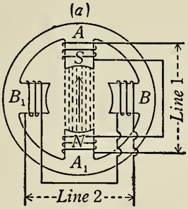


FIG. 386. A rotating magnetic field produced by two currents 90° apart

rotate with it. This would then be a two-phase motor. Precisely similarly a three-phase current passing through the coils surrounding the soft-iron ring shown in Fig. 387 actually creates, in that soft iron, poles which rotate around the ring and a corresponding field which rotates inside the ring so as to drag the rotor with it.

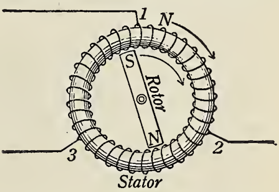


FIG. 387. Three-phase circuit

[**The induction motor.** The stator of the induction motor has a rotating magnetic field created within it precisely in the way just described with reference to Fig. 386. But the rotor, instead of being a permanent magnet, in its simplest form is a *squirrel cage* made of heavy parallel bars of copper soldered to solid-copper end plates (Fig. 388). The lines of force of the rotating magnetic field (Fig. 387) are continuously cutting these conductors and thus setting up huge currents which by the dynamo rule are seen to flow lengthwise of the bars, through the end plates and back through the bars on the opposite side of the rotor. Since the resistance of this circuit is exceedingly low, these induced

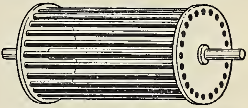


FIG. 388. The squirrel-cage rotor

currents are very large. The rotating magnetic field reacts upon them in just the way in which in any motor the stationary magnetic field reacts on the current sent through the armature, as described on page 404. (See also page 394.) The speed of rotation of the squirrel cage must evidently lag somewhat behind the speed of rotation of the field; otherwise there would be no cutting of lines of force by the bars of the armature and hence no induced current for the field to react upon.

Summary. Impedance is the total resistance to the flow of an alternating current. An iron core increases very largely the impedance of a coil because it increases the number of magnetic lines that thread the coil. A coil with large impedance is called a choke coil.

In alternating-current circuits watts = volts × amperes × power factor.

An alternating current appears to flow through a condenser, though the circuit is open.

Most large power installations generate three-phase currents. Such currents, when passed through the stator of an induction motor, produce a rotating magnetic field. Such a field induces large currents in the rotor of the induction motor, and the reaction of the field on these currents causes the rotation, though there is no metallic connection at all between the stator and the squirrel-cage armature.

QUESTIONS AND PROBLEMS

1. When does Ohm's law in its ordinary form apply to alternating-current circuits?

2. How would you make an effective choke coil?

3. (*a*) What is the difference between a single-phase and a three-phase generator? (*b*) What makes the rotor of an induction motor turn?

4. Does the rotor of an induction motor revolve as rapidly as the rotating field?

5. What kind of motor would run a sewing machine in an ordinary house?

UNIT FIVE

Wave Motion and Sound

There are probably no phenomena that play so large a role in everyday life as the phenomena of sound. Think what a world without sound would be — no talking, no birdcalls, no music, no telephones, no radios! And yet how many of us have any understanding of what makes the difference between the innumerable varieties of sound we hear?

In spite of the part sound has played from the earliest times in the life of man, strangely enough it was not until the time of Helmholtz, who died as recently as 1895, that the first steps were taken toward understanding so simple a thing as why the quality of one sound differs from that of another.

People have known for a long time that some rooms were good and some very bad for the purposes of music and speech, but just what made the difference they did not know. How to set about building a room of desirable sound qualities is an art that has been developed only within the present century.

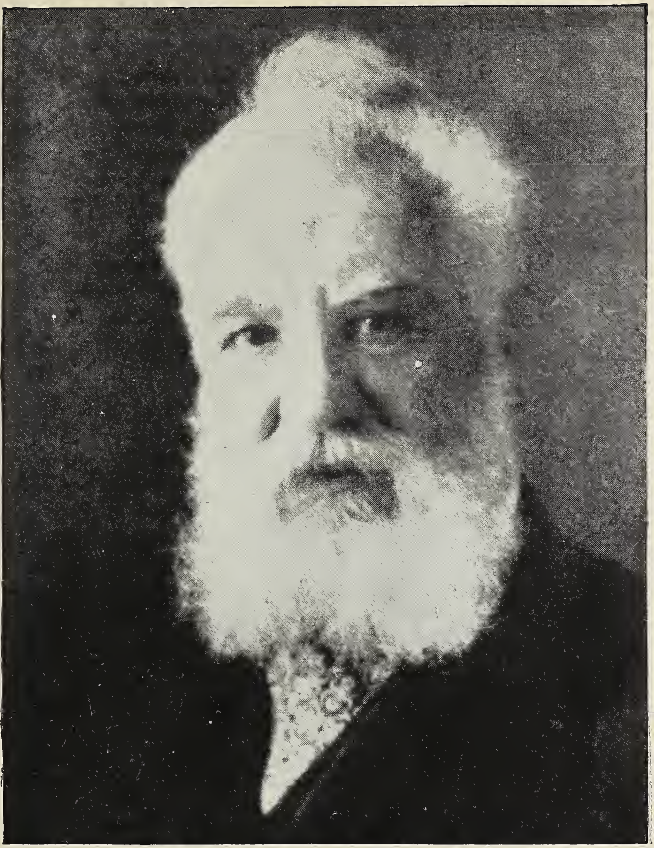
It is only within the past fifteen years that the phonograph and the sound motion picture have been so perfected that from now on the world's great leaders will appear in person before all the following generations of men and talk to them just as the living now talk to us.

The new electrical methods for the production of organ music, brought before the public in a practical way for the first time in the year 1935, have in them

the possibility of spreading a knowledge and appreciation of music to a greatly increased number of our population.

The fact that year in and year out more than fifty million tickets are bought each week at the box offices of the motion-picture houses of the United States reveals the stupendous social effect which recent technical developments in the field of sound are having upon the life of modern man.

It is not too much to say that the modern development of the science and art of the transmission and reproduction of sound constitutes one of the most spectacular contributions that physics has made to the progress of civilization. It is the fundamental principles underlying this science that are found in the following pages.



Alexander Graham Bell (1847–1922)

The recent enormous advances in both our knowledge and our use of sound have been largely due to Bell's fundamental discovery that sound waves can be translated into electric currents of the same wave form. This portrait of the inventor of the telephone was transmitted 3305 miles over the wire and reproduced by the aid of the photoelectric cell, a device embodying our latest knowledge of the properties of the electron. (See also Chapter XXIII)

Hermann Ludwig Ferdinand von Helmholtz (1821–1894)

The development of the fundamental principles underlying our knowledge of sound is due very largely to this noted German physicist and physiologist. He was professor of physiology and anatomy at Bonn and at Heidelberg from 1855 to 1871; professor of physics at Berlin from 1871 to 1894; published in 1847 a famous paper on the conservation of energy, which was most influential in establishing that doctrine; invented the ophthalmoscope; discovered the physical significance of tone quality, and made other very important contributions to both acoustics and optics; was pre-eminent also as a mathematical physicist

CHAPTER XVI

Nature and Transmission of Sound*

Speed and Nature of Sound

Sources of sound. If a sounding tuning fork provided with a stylus is stroked across a smoked-glass plate, it produces a wavy line, as shown in Fig. 389; if a light suspended ball is brought into contact with it, the latter is thrown off with considerable violence. If we look about for the source of any sudden noise, we find that some object has fallen, or some collision has occurred, or some explosion has taken place — in a word, that some violent motion of matter has been set up in some way. From these familiar facts we conclude that *sound arises from the motions of matter.*

FIG. 389. Trace made by vibrating fork

Media of transmission. Air is ordinarily the medium through which sound comes to our ears; yet an Indian puts his ear to the ground to hear a distant noise, and most boys know how loud the clapping of stones sounds under water. If a very long rod is pressed against a blackboard, and the stem of a vibrating tuning fork pressed against the outer end, a loud sound will come from the blackboard. If the base of the sounding fork of Fig. 389, fitted to a piece of wood, is held in a dish of water, the sound will be markedly transmitted by

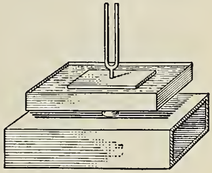


FIG. 390. Transmission of sound through water

* This chapter should be accompanied by laboratory experiments on the speed of sound in air, the vibration rate of a fork, and the determination of wave lengths. See, for example, Experiments 50, 51, and 52 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

the water to a resonance box (Fig. 390). These facts show that a gas like air certainly transmits sound no more easily than a liquid or a solid. Next let us see whether or not matter is necessary at all for the transmission of sound.

Suspend an electric bell inside the receiver of an air pump by means of two fine springs which pass through a rubber stopper in the manner shown in Fig. 391. Exhaust the air from the receiver by means of the pump. The sound of the bell will be found to become less and less pronounced. Suddenly readmit the air. The volume of sound will at once increase.

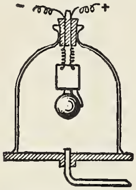


FIG. 391. Sound not transmitted through a vacuum

Since the nearer we approach a vacuum, the less distinct becomes the sound, we infer that sound cannot be transferred through a vacuum and that therefore *sound can be transmitted only through some kind of ordinary matter.* In this respect sound differs from heat and light, which evidently pass with perfect readiness through a vacuum, since they reach the earth from the sun and stars.

Speed of transmission. Anyone who has seen a lightning flash and then waited to hear the thunder knows that sound travels much more slowly than light. The first attempt to measure accurately the speed of sound was made in 1738, when a commission of the French Academy of Sciences stationed two parties about seventeen or eighteen miles apart and observed the interval between the flash of a cannon and the sound of the report. The time taken for light to travel this distance (speed of light = 186,000 miles per second) is wholly negligible. By taking observations between the two stations, first in one direction and then in the other, the effect of the wind was eliminated. A second commission repeated these experiments in 1832, using a distance of 18.6 kilometers, or a little more than 11.5 miles. The value found was 331.2 meters per second at 0° C. The accepted value is now 331.3 meters per second. The speed in water is about four and four-tenths times as great and in iron over sixteen times as great.

The speed of sound in air is found to increase with an increase in temperature. The amount of this increase is about 2 feet per second per degree centigrade. It is sufficiently accurate to remember 1090 feet per second at 0° C. (= 32° F.), or 1130 feet per second at 20° C. (= 68° F.).

How sound travels. When a firecracker or toy cap explodes, the powder is suddenly changed to a gas, the volume of which is enormously greater than the volume of the powder. The air is therefore suddenly pushed back in all directions from the center of the explosion. This means that the air particles which lie about this center are given violent outward velocities.* When these outwardly pushed air particles collide with other particles, they give up their outward motion to these second particles, and these in turn pass it on to others, etc. It is clear, therefore, that the motion started by the explosion must travel on from particle to particle to an indefinite distance from the center of the explosion. (See opposite pages 443 and 504.) Furthermore, it is also clear that, although the motion travels on to great distances, the individual particles do not move far from their original positions; for it is easy to show experimentally that whenever an elastic body in motion collides with another similar body at rest, the colliding body simply transfers its motion to the body at rest and comes itself to rest.

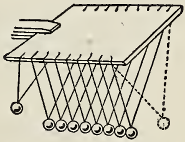


Fig. 392. Illustrating the propagation of sound from particle to particle

Hang six or eight equal steel balls from cords in the manner shown in Fig. 392. First hold all the balls but two adjacent ones to one side, and raise one of these two and allow it to fall against the other. The first ball will be found to lose its motion in the collision, and the second will be found to rise to practically the same height as that from which the first

* These outward velocities are simply superposed upon the velocities of agitation which the molecules already have on account of their temperature. For our present purpose we may ignore entirely the existence of these latter velocities and treat the particles as though they were at rest, save for the velocities imparted by the explosion.

fell. Next place all the balls in line and raise the end one and allow it to fall as before. The motion will be transmitted from ball to ball, each giving up the whole of its motion practically as soon as it receives it, and the last ball will move on alone with the velocity which the first ball originally had.

The preceding experiment furnishes a very nice mechanical illustration of the manner in which the air particles which receive motions from an exploding firecracker or a vibrating tuning fork transmit these motions in all directions to neighboring layers of air, these in turn to the next adjoining layers, etc., until the motion has traveled to very great distances, although the individual particles themselves move only very minute distances. When a motion of this sort, transmitted by air particles, reaches the drum of the ear, it produces the sensation which we call *sound.* In physics, however, the word *sound* means not the sensation but rather the wave motion capable of producing it.

Wave motion. Wave motion is not found in sound phenomena only. Indeed, it is probably the most fundamental way in which energy is transferred from one place to another. We have all watched water waves; light comes to us in waves; heat is transferred from place to place by means of waves; millions of people all over the country are listening to concerts, speeches, and plays that come to them in the form of radio waves. These different kinds of waves have many different properties, but they all have certain properties in common. We will examine these common properties of all wave motion, noting especially the particular form of wave motion we call sound.

Put a small piece of cork on the surface of a body of water in the path of an advancing wave. The cork will not be carried along by the wave, but will remain in the same place, riding up over the top of the wave and down the other side as the wave passes.

The cork, being very light, moves about as the water particles move. Thus we see that in a water wave, as in the wave illustrated in Fig. 393, the particles making up the wave

do not themselves move great distances, but rather move short distances, then transmit their motion to other particles and move back into place again.

Transverse and longitudinal waves. We notice one important difference, however, between the water wave and the wave transmitted through the steel balls. In the former the individual particles move up and down *perpendicular* to the line of motion of the wave (Fig. 393), whereas in the latter the particles move back and forth *in line with* the motion of the wave. These are the two fundamental kinds of waves. Those like water waves are called *transverse* waves; the other kind are called *longitudinal*, or *compressional*, waves. A simple demonstration will make the difference clear.

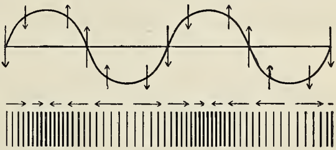


FIG. 393. Transverse and longitudinal waves

Attach one end of a long wire spring to the wall (Fig. 394). Stretch the spring taut from the wall and give the free end of it a quick vertical shake with the hand. A transverse wave will travel

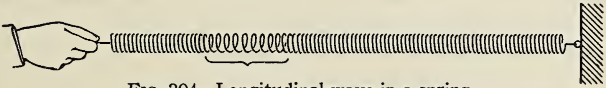


FIG. 394. Longitudinal wave in a spring

along the spring to the wall and be reflected back again. Now compress a small portion of the spring near the hand and suddenly let it go. A longitudinal wave will travel along the spring.

Sound waves are of the longitudinal, or compressional, type.

Trains of waves. In most wave phenomena we are interested not in a single wave pulse, such as we have discussed above, but in a whole train of such waves following one another usually at regular intervals. The nature of such a continuous train, in this case of sound waves, may be very simply and beautifully shown by the so-called manometric flames. (See opposite page 442.)

First rotate the mirror when no note is sounded before the mouthpiece. There will be no fluctuations in the flame, and its image, as seen in the moving mirror, will be a straight band, as shown in *2*. Next sound a mounted C fork or produce some other simple tone in front of *G*. The image in the mirror will be that shown in *3*. Then sound another fork having twice as many vibrations per second in place of the C. The image will be that shown in *4*. The images of the flame are now twice as close together as before, since the blows strike the diaphragm twice as often.*

When the note was produced before the mouthpiece *G*, the up-and-down motions of the flame observed in the revolving mirror were due to variations in the pressure of the gas coming to the flame through the chamber *B*. These variations in pressure were the direct result of vibrations of the diaphragm which could have been caused in no other way than by a regular succession of air pulses striking upon it.

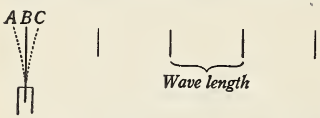


FIG. 395. Vibrating prong sending out a train of equidistant pulses

How these pulses are set up may be easily seen by analyzing the motion of the prong of Fig. 395. As this prong moves steadily to the right, it compresses the air in front of it more and more. This in turn exerts pressure on the air a little farther to the right, and as this pressure is transmitted from layer to layer, a wave of compression travels away from the prong. As this compression wave leaves the prong, the prong moves back from right to left, tending to leave a vacuum behind it. The air particles next the prong rush back to the left, again producing a region of *rarefaction*, or low density, which follows the compressional wave to the right. The prong then returns, sending out another compressional wave, and so on. As shown in Fig. 395, the distance between corresponding points in two adjacent compressions is a wave length.

* If a rotating mirror is not to be had, a piece of ordinary mirror glass held in the hand and oscillated back and forth about a vertical axis will be found to give satisfactory results.

These two pulses of condensation and rarefaction make up a complete wave. When the fork is vibrating continuously,

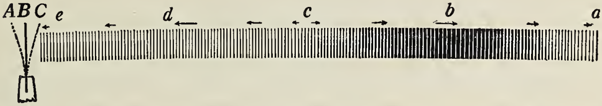


FIG. 396. Illustrating motions of air particles in one complete sound wave consisting of a condensation and a rarefaction

it sends out a continuous train of such waves. Fig. 396 shows a sound wave and the directions in which the particles are moving at a given instant.

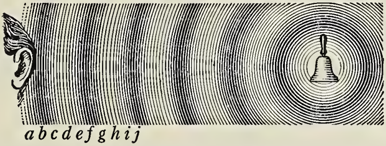


FIG. 397. Illustration of sound waves

Graphic representation of sound waves. For simplicity sound and other longitudinal waves are usually represented graphically as if they were transverse waves. Thus in Fig. 398 the crests (*A–C*, *E–G*, etc.) represent condensations; the

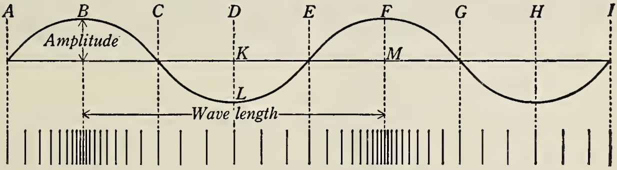


FIG. 398. Graphical representation of sound waves

troughs (*C–E*, *G–I*, etc.) represent rarefactions. Points *A*, *C*, *E*, *G*, and *I* represent points of normal density, *B* and *F* those of maximum density, and *D* and *H* those of minimum density.

Wave length, velocity, and frequency. In any sort of wave motion the *wave length* is the length of a complete wave. In a transverse wave it is the distance from crest to crest or from trough to trough, in a longitudinal wave the distance from one point of maximum condensation to the next, or in general the distance between any point and the nearest point in the same condition, or *phase*, of disturbance (for example, A–E, B–F, D–H).

The *velocity* of a wave or train of waves is the rate of motion of a crest or point of maximum condensation such as B.

The *frequency* of a wave train is the number of complete waves which pass a stationary point in one second.

The relationship between these three quantities may be easily seen from an example. Suppose a tuning fork makes 110 complete vibrations per second. At the end of 1 second the first wave will have traveled 1100 feet. There will then be 110 waves equally spaced in this distance. Each wave must then be 10 feet long.

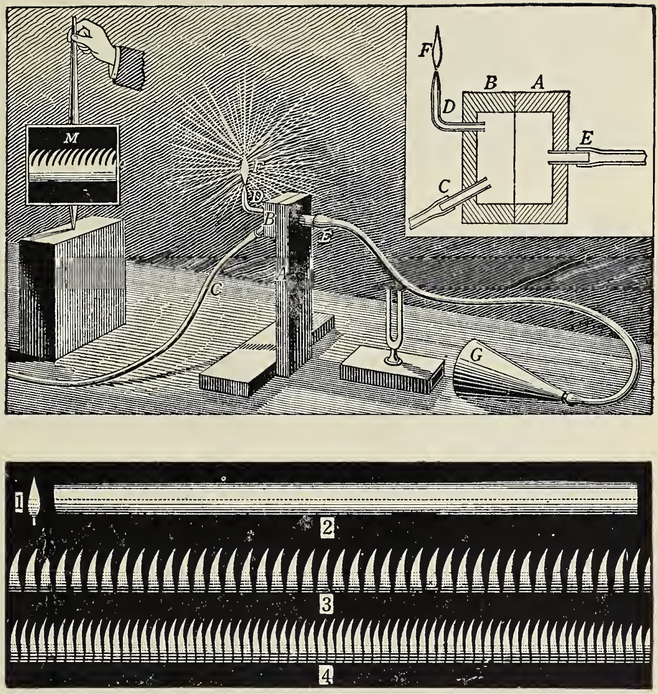
Algebraically, if n is the frequency, l the wave length, and v the velocity, it is evident that the relation is

$$l = \frac{v}{n}, \text{ or } v = nl;$$

that is, *wave length is equal to velocity divided by the number of vibrations per second, or velocity is equal to the number of vibrations per second multiplied by the wave length.*

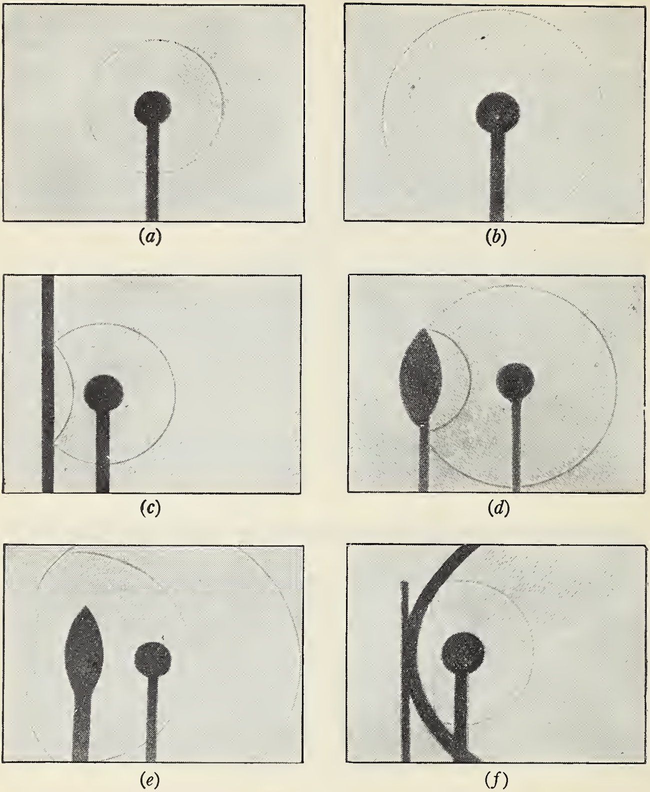
Since this relation is a general one which holds for all waves, it is very important in the study of light, radio, and all other wave phenomena.

Distinction between musical sounds and noises. Direct a current of air from a $\frac{1}{8}$-inch nozzle against a row of forty-eight equidistant $\frac{1}{4}$-inch holes in a metal or cardboard disk, mounted as in Fig. 399, and set into rotation either by hand or by an electric motor. A very distinct musical tone will be produced. Then direct the jet of air against a second row of forty-eight holes, which differs from the first only in that the holes are spaced irregularly instead of regularly about the circumference of the disk. The musical character of the tone will altogether disappear.



Manometric Flames

This device consists of the following parts: a chamber in the block *B*, through which gas is led by way of the tubes *C* and *D* to the flame *F*; a second chamber in the block *A*, separated from the first chamber by an elastic diaphragm made of very thin sheet rubber or paper and communicating with the source of sound through the tube *E* and trumpet *G*; and a rotating mirror *M* by which the flame is observed. With constant speed of rotation the number of teeth per inch gives the pitch of the sound. Quality is also analyzed by the manometric flame, as shown on page 465



Photographs of Sound Waves Having their Origin in an Electric Spark behind the Middle of the Black Disk

(*a*) A spherical sound wave. (*b*) The same wave .00007 second later. (*c*) A wave reflected from a plane surface, curvature unchanged. (*d*) A wave reflected from a convex surface, curvature increased. (*e*) The source at the focus of an SO_2 lens: the photograph shows, first, the original wave on the right; second, the reflected wave, with its increased curvature; and third, the transmitted plane wave. (*f*) Source at focus of a concave mirror; the reflected wave is plane. (Taken by Professor A. L. Foley and Wilmer H. Souder, of the University of Indiana)

The experiment furnishes a very striking illustration of the difference between a musical sound and a noise. *Sounds possess a musical quality only if their frequency is regular, that is, if the pulses or waves which make them up are sent out at absolutely regular intervals.*

Pitch. While the apparatus of the preceding experiment is rotating at constant speed, direct a current of air first against the outside row of regularly spaced holes and then suddenly against the inside row, which is also regularly spaced but which contains a smaller number of holes. The note produced in the second case will be found to have a markedly lower pitch than the other one. Again direct the jet of air against one particular row and increase the speed of rotation. The note produced will gradually rise in pitch.

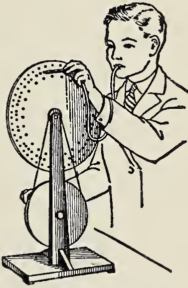


FIG. 399. Regularity of pulses the condition for a musical tone

We conclude, therefore, that *the pitch of a musical note depends simply upon the number of pulses which strike the ear per second, that is, upon the frequency of the wave train.* If the sound comes from a vibrating body, *the pitch of the note depends upon the rate of vibration of the body, and this in turn determines the length of the wave as shown by the relation $v = nl$.*

It is interesting to note that some bodies vibrate so rapidly that the waves reaching the ear are not able to produce the sensation of sound. On the other hand, some vibrations are so slow that the eardrum does not translate them into sound. The limits of audibility vary somewhat with different persons, but in general are between 16 and 16,000 vibrations per second.

[**The Doppler effect.** When a rapidly moving train rushes past an observer, he notices a very distinct and sudden change in the pitch of the bell as the engine passes him, the pitch being higher as the engine approaches than as it recedes. The explanation is as follows: The bell sends out pulses at

exactly equal intervals of time. As the train is approaching, however, the pulses reach the ear at shorter intervals than the intervals between emissions, since the train comes toward the observer between two successive emissions. But as the train recedes, the interval between the receipt of pulses by the ear is longer than the interval between emissions, since the train is moving away from the ear during the interval between emissions. Hence the pitch of the bell is higher during the approach of the train than as it recedes. This phenomenon of the change in pitch of a note proceeding from an approaching or receding body is known as *the Doppler effect.*

Loudness. The loudness, or intensity, of a sound depends upon the rate at which energy is communicated by it to the eardrum; that is, under the usual condition of hearing, *loudness depends upon the amplitude of the forward and backward motion of the air lying close to the drum of the ear*, and this in turn is determined by the distance of the source and the *amplitude* of its vibration, provided the sound is transmitted through a still, uniform medium. In Fig. 398 the amplitude of the wave is represented by the distance KL or FM, that is, the maximum displacement of any particle from its normal position.

If a given sound pulse is free to spread equally in all directions, at a distance of 100 feet from the source the same energy must be distributed over a sphere of four times as large an area as at a distance of 50 feet. Hence under these ideal conditions *the intensity of a sound varies inversely as the square of the distance from the source.* But when sound is confined within a tube so that the energy is continually communicated from one layer to another of equal area, it will travel to great distances with little loss of intensity. This explains the efficiency of speaking tubes and megaphones.

Summary. **All sounds arise from motion of matter.**

Sound is transmitted by solids, liquids, and gases, but not through a vacuum.

Relation of velocity, wave length, and frequency is given by $v = nl$.

Musical sounds come from regularity of vibration; noises, from irregular pulses.

Pitch depends upon number of vibrations per second.

Loudness depends upon the amplitude of the vibrations.

QUESTIONS AND PROBLEMS

A

1. When a long column of marchers is following a band, it is observed that those in the rear of the column are slightly out of step with those in front. Explain.

2. A thunderclap was heard $5\frac{1}{2}$ sec after the accompanying lightning flash was seen. How far away did the flash occur, the temperature at the time being 20° C.?

3. Since the music of an orchestra reaches a distant hearer without confusion of the parts, what may be inferred as to the relative velocities of the notes of different pitch?

4. If we increase the amplitude of vibration of a guitar string, what effect has this (*a*) upon the amplitude of the wave? (*b*) upon the loudness? (*c*) upon the length of the wave? (*d*) upon the pitch?

5. Why does the sound die away very gradually after a bell is struck?

6. Explain the principle of the ear trumpet.

7. How would the intensity of the sound of a bell heard by a man 1000 ft away compare with the intensity of the sound heard by a man 2000 ft away if no reflections of the sound took place?

8. Why does placing the hand behind the ear enable a partially deaf person to hear better?

9. What is the relation between pitch and wave length?

10. A bullet fired from a rifle with a speed of 1200 ft/sec is heard to strike the target 6 sec afterward. What is the distance to the target, the temperature of the air being 20° C.? (Let $x =$ the distance to the target.)

B

1. A blow struck with a hammer on a steel cable was heard through the cable in 0.2 sec and through the air 2.8 sec later. The temperature was 18° C. (*a*) How far away was the blow struck? (*b*) What was the velocity of sound in the cable?

2. If the tone of a man's voice has a frequency of 120, how long are the waves which are produced when he speaks in air at a temperature of 20° C.?

3. What is the relative loudness of the sound of the discharge of a gun as heard by A a mile from the gun and as heard by B a quarter of a mile from the gun?

4. Explain why the pitch of a locomotive whistle or of an automobile horn suddenly becomes lower just after the locomotive or automobile rushes past you.

5. Stations A, B, and C are one mile apart in a straight line. An enemy's cannon is heard at A and C at the same instant, but 2 sec sooner at B. Locate the cannon with reference to these three points, the temperature being 20° C.

6. If the lowest tone which the ear can recognize has a frequency of 16 vibrations per second, what is the length of the longest wave the ear perceives in air at a temperature of 0° C.?

7. What happens to the music when we speed up the phonograph motor? Explain the principle of physics involved.

Reflection, Reinforcement, and Interference

Echo. Just as a rubber ball when thrown at a hard surface bounces back, so too a sound wave hitting a wall is reflected, as is shown by the familiar phenomenon of echo. Part of the energy of the wave is always lost by absorption at the reflecting surface, and another part in traveling to the reflecting surface and back. Therefore the amplitude of the reflected wave is less than that of the original, and the echo is never as loud as the original sound. The roll of thunder is caused by successive reflections of the original sound from clouds and other surfaces which are at different distances from the observer.

Occasionally, in very large rooms, echoes can be heard distinct from the original sound, but in smaller rooms the two blend together. The effect of a sound on the ear lasts for about a tenth of a second after the waves have stopped striking it. An echo must thus return more than a tenth of a second after the original sound has struck the ear to be

heard separately. Since sound travels a little more than 100 feet in a tenth of a second, the reflecting surface must be at least 50 feet away.

In a small room the sound is reflected from walls, floor, and ceiling again and again; in this way the room is filled with sound, which gradually dies away as the walls absorb it. Since this *reverberation* strengthens the original sound, it is desirable so long as it does not interfere with succeeding sounds. The best time of reverberation of a room for piano music has been set at about 1 second. Engineers have developed very accurate methods of determining the time, intensity, and quality of reverberation, and by the use of various kinds of absorbent materials rooms can now be designed to give just the proper amount of reverberation. Sound motion pictures have made acoustic engineering an important part of theater and auditorium architecture.

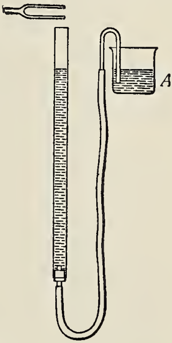


FIG. 400. Illustrating resonance

On ships the depth of the ocean bottom is commonly determined by a "fathometer," a device which automatically translates into depth the time required for an echo to come back from the bottom.

Whispering galleries, such as the dome of the Capitol at Washington, are merely rooms so shaped that sound foci are produced by the concentration of waves reflected from the walls.

Resonance. Resonance is the *reinforcement* or *intensification* of sound because of the union of *direct* and *reflected* waves.

Thus hold one prong of a vibrating tuning fork, which makes, for example, 512 vibrations per second, over the mouth of a tube an inch or so in diameter, arranged as in Fig. 400, so that as the vessel *A* is raised or lowered the height of the water in the tube may be adjusted at will. It will be found that as the position of the water is slowly lowered from the top of the tube a very marked reinforcement of the sound will occur at a certain point.

Try other forks of different pitch in the same way. It will be found that the lower the pitch of the fork, the lower must be the water in the tube in order to get the best reinforcement. This means that the longer the wave length of the note which the fork produces, the longer must be the air column in order to obtain resonance.

We conclude, therefore, that a *fixed relation exists between the wave length of a note and the length of the air column which will reinforce it.*

Fig. 401. Resonant length of a closed pipe is one-fourth wave length

Best resonant length of a closed pipe. If we calculate the wave length of the note of the fork by dividing the speed of sound by the vibration rate of the fork, we shall find that, in every case, *the length of air column which gives the best response is approximately one-fourth wave length.* The reason for this is evident when we consider that the length must be such as to enable the reflected wave to return to the mouth just in time to unite with the direct wave which is at that instant being sent off by the prong. Thus, when the prong is first starting down from the position A (Fig. 401), it starts the beginning of a condensation down the tube. If this motion is to return to the mouth just in time to unite with the direct wave sent off by the prong, it must get back at the instant the prong is starting up from the position C. That is, the pulse must go down the tube and come back again while the prong is making a half-vibration. This means that the path down and back must be a half wave length, and hence that the length of the tube must be a fourth of a wave length.

From the above analysis it will appear that there should also be resonance if the reflected wave does not return to the mouth until the fork is starting back the second time from C, that is, at the end of one and one-half vibrations instead of a half-vibration. The distance from the fork to the water and back would then be one and one-half wave lengths; that is, the water surface would be one-half wave length farther down

the tube than at first. The tube length would, therefore, now be three fourths of a wave length.

Try the experiment. A similar response will be found, as predicted, a half wave length farther down the tube. This response will be somewhat weaker than before, as the wave has lost some of its energy in traveling a longer distance through the tube. It may be shown in a similar way that there will be resonance where the tube length is $\frac{5}{4}$, $\frac{7}{4}$, or indeed any odd number of quarter wave lengths.

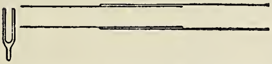


FIG. 402. Resonant length of an open pipe is one-half wave length

Best resonant length of an open pipe. Hold the same tuning fork which was used in the demonstration on page 447 in front of an open pipe 8 or 10 in. long, the length of which is made adjustable by slipping back and forth over it a tightly fitting roll of writing paper (Fig. 402). It will be found that for one particular length this open pipe will respond quite as loudly as did the closed pipe, but *the responding length will be found to be just twice as great as before.* Other resonant lengths can be found when the tube is made twice, three times, etc. as long.

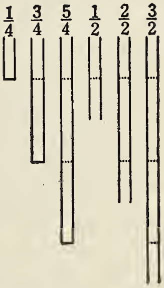


FIG. 403. Closed and open pipes which respond to the same fork

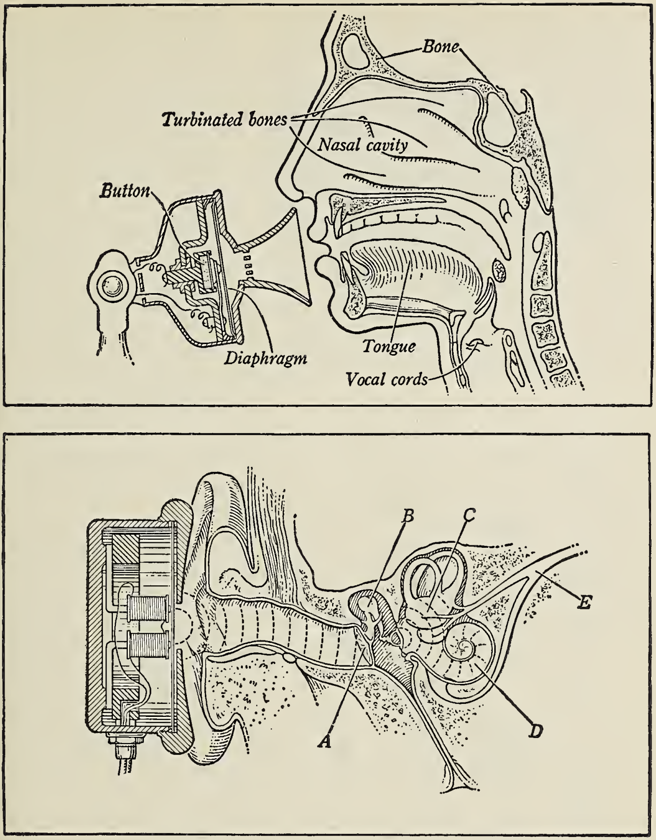
We learn, then, that *the shortest resonant length of an open pipe is one-half wave length, and that there is resonance at any multiple of a half wave length.*

Thus the shortest resonant length of the open pipe is just twice that of the closed one. This means that when a condensation reaches the end of an open pipe, it is reflected back not as a condensation but as a rarefaction. In other words, when the lower end of the tube of Fig. 401 is open, a condensation upon reaching it suddenly expands. In consequence of this expansion the new pulse which begins at this instant to travel back through the tube is one in which the particles are moving down instead of up; that is, the particles are moving in a direction opposite to that in which the wave is

traveling. This is always the case in a rarefaction. (See Fig. 396.) In order, then, to unite with the motion of the prong, this downward motion of the particles must get back to the mouth when the prong is just starting down from A the second time, that is, *after one complete vibration of the prong.* This shows why the pipe length is one-half wave length. Fig. 403 summarizes what we have learned concerning the lengths of both closed and open pipes.

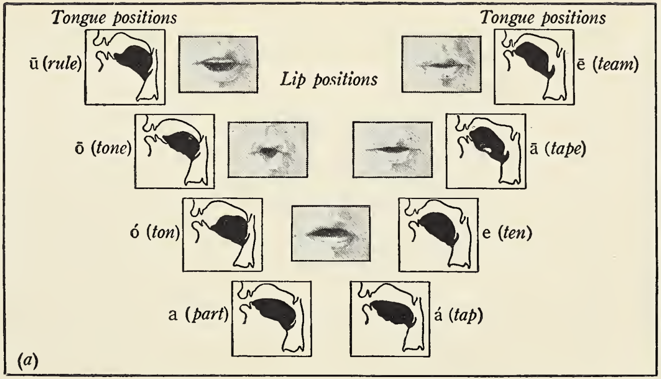
Resonators. If the vibrating fork at the mouth of the tubes in the preceding experiments is replaced by a *train of waves* coming from a distant source, precisely the same analysis tells us that the waves reflected from the bottom of the tube will reinforce the oncoming waves when the length of the tube is any odd number of quarter wave lengths in the case of a closed pipe, or any number of half wave lengths in the case of an open pipe. It is clear, therefore, that every air chamber will act as a resonator for trains of waves of a *certain* wave length. This is why some shells held to the ear are always heard to hum with a particular note. Feeble waves which produce no impression upon the unaided ear gain sufficient strength when reinforced by the shell to become audible. When the air chamber is of irregular form it is not usually possible to calculate to just what wave length it will respond, but it is always easy to determine experimentally what particular wave length it is capable of reinforcing. The resonators on which tuning forks are mounted are air chambers which are of just the right dimensions to respond to the note given out by the fork.

Forced vibrations; sounding boards. Strike a tuning fork and hold it in the hand. The sound will be entirely inaudible except to those quite near. Press the base of the sounding fork firmly against a table. The sound will be found to be greatly intensified. Hold another sounding fork of different pitch against the same table. Its sound will also be reinforced. In this case, then, the table intensifies the sound of any fork which is placed against it, whereas an air column of a certain size can intensify only a single note, or several notes related in the manner indicated in the preceding pages.



The Organs of Speech and Hearing

The sound waves produced by the vocal cords and mouth cavity are transmitted from the receiver diaphragm through the air to the eardrum *A*, which communicates them to the chain of bones (hammer, anvil, and stirrup) *B*. This in turn passes them on to the fluid *C* of the inner ear, through which they reach the nerve fibers *D*, each supposed to be tuned to a particular frequency. The nerve filaments all unite in the auditory nerve *E*, leading to the brain. (Courtesy of the Bell Telephone Laboratories)



(*a*) *How Speech is Produced;* (*b*) *Bellows Forces Air through Artificial Larynx*

The intelligibility of speech is determined primarily by the way the stream of air from the lungs passes through the mouth cavity and out past the tongue, lips, and teeth. This was shown strikingly when the Bell Laboratories developed their artificial larynx, which enables hundreds of people in the United States who have entirely lost their vocal cords to learn to converse intelligibly. In this instrument is a thin metal reed, such as is used in a mouth organ, which replaces the lost vocal cords. It is placed within a small tube, through which air is forced, either from the lungs or from a bellows (*b*). The sounds coming from this reed are not recognizable as speech at all; but when this tube from which they are issuing is introduced into the mouth of the speaker, the resonating action of his mouth, throat, and nasal cavities manufactures out of the basic sound produced by the reed the so-called voiced speech sounds, mainly vowels (*a*). The so-called unvoiced sounds, mainly consonants (see opposite page 467), are produced by simply blowing air through the artificial larynx without throwing the reed into vibration, and then modifying this air stream, as in whispering, with the tongue, lips, and teeth. (Courtesy of the Bell Telephone Laboratories)

The cause of the response in the two cases is wholly different. In the last case the vibrations of the fork are transmitted through its base to the table top and force the latter to vibrate in the period of the fork. The vibrating table top, on account of its large surface, sets a comparatively large mass of air into motion and therefore sends a wave of great intensity to the ear, but the fork alone, with its narrow prongs, was not able to impart much energy to the air. Vibrations like those of the table top are called *forced* because they can be produced with any fork, no matter what its period. Sounding boards in pianos and other stringed instruments act precisely as does the table top in this experiment; that is, they are set into forced vibrations by any note of the instrument and reinforce it accordingly.

Beats. Since two sound waves are able to unite so as to reinforce each other, it ought also to be possible to make them unite so as to interfere with or destroy each other. In other words, under the proper conditions *the union of two sounds ought to produce silence.*

Set two mounted tuning forks of the same pitch side by side, as in Fig. 404. Strike the two forks in quick succession with a soft mallet — for example, a rubber stopper on the end of a rod. The two notes will blend and produce a smooth, even tone. Then stick a piece of wax or a small coin to a prong of one of the forks. This diminishes slightly the number of vibrations which this fork makes per second, since it increases its mass. Again, sound the two forks together. The former smooth tone will be replaced by a throbbing, or pulsating, one. This is caused by the alternate destruction and reinforcement of the sounds produced by the two forks. This pulsation is called the phenomenon of *beats*.

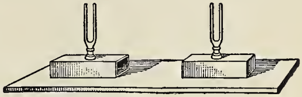


FIG. 404. Arrangement of forks for beats

The mechanism of the alternate destruction and reinforcement may be understood from the following: Suppose that one fork makes 256 vibrations per second (see the dotted line *AC* in Fig. 405), while the other makes 255 (see the heavy line

AC). If at the beginning of a given second the two forks are swinging *together*, so that they simultaneously send out condensations to the observer, these condensations will of course unite so as to produce a double effect upon the ear (see *A′*, Fig. 405). Since one fork gains one complete vibration per second over the other, at the end of the second considered the two forks will again be vibrating together, that is, sending out condensations which add their effects as before (see *C′*).

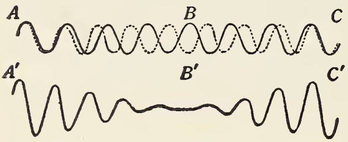


FIG. 405. Graphic illustration of beats

In the middle of this second, however, the two forks are vibrating in opposite directions (see *B*); that is, one is sending out rarefactions while the other sends out condensations. At the ear of the observer the union of the rarefaction (backward motion of the air particles) produced by one fork with the condensation (forward motion) produced by the other results in no motion at all, if the two motions have the same amplitude; that is, *in the middle of the second the two sounds have united to produce silence* (see *B′*). Obviously *the number of beats per second is equal to the difference in the vibration numbers of the two forks.*

To test this conclusion, add more wax or a heavier coin to the weighted prong; the number of beats per second will be increased. Diminishing the weight will reduce the number of beats per second.

In tuning a piano the double and triple strings are brought into unison by tuning so as to eliminate beats. The superheterodyne circuit as employed in most modern radios uses the principle of beats in its operation.

Interference of sound waves by reflection. Attach a thin cork about 1 in. in diameter to one end of a brass rod from 1 to 2 m long. Clamp this rod firmly in the middle (Fig. 406). Put some cork dust in a piece of glass tubing 1 m or more long and from 1 in. to $1\frac{1}{2}$ in. in diameter and slip the tube over the cork. Stroke the end of the rod longitudinally with a well-resined cloth. A loud, shrill note will be produced.

This note is produced by the slipping of the resined cloth over the surface of the rod, which sets the latter into longitudinal vibrations, so that its ends impart alternate condensations and rarefactions to the layers of air in contact with them. As soon as this note is started, the cork dust inside the tube will be seen to be intensely

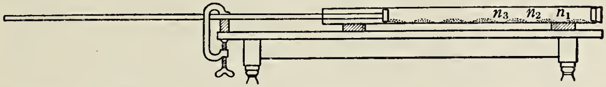


FIG. 406. Interference of advancing and retreating trains of sound waves

agitated. If the effect is not marked at first, a slight slipping of the glass tube forward or back will bring it out. Upon examination it will be seen that the agitation of the cork dust is not uniform, but at regular intervals throughout the tube there will be regions of complete rest, n_1, n_2, n_3, etc., separated by regions of intense motion.

The points of rest correspond to the positions in which the reflected train of sound waves returning from the end of the tube neutralizes the effect of the advancing train passing down the tube from the vibrating rod. The points of rest are called *nodes*, the intermediate portions *loops*, or *antinodes*. The distance between these nodes is one-half wave length, for at the instant that the first wave front a_1 (Fig. 407) reaches the end of the tube it is reflected and starts back toward R. Since at this instant the second wave front a_2 is just one wave length to the left of a_1, the two wave fronts must meet each other at a point n_1, just one-half wave length from the end of the tube. The exactly equal and opposite motions of the particles in the two wave fronts exactly neutralize each other. Hence the point n_1 is a point of no motion, that is, a node. Again, at the instant that the reflected wave front a_1 meets the advancing wave front a_2 at n_1, the third wave front a_3 is just one wave length to the left of n_1. Hence, as the first wave front a_1 continues to travel back toward R it meets a_3 at n_2, just one-half wave length

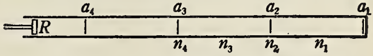


FIG. 407. Distance between nodes is one-half wave length

from n_1, and produces there a second node. Similarly a third node is produced at n_3, one-half wave length to the left of n_2, etc. Thus *the distance between two nodes must always be just one half the wave length of the waves in the train.*

In the preceding discussion it has been assumed that the two oppositely moving waves are able to pass through each other without either of them being modified by the presence of the other. That two opposite motions are transferred in just this manner through a medium consisting of elastic particles may be shown by the following experiment with the row of balls used in the demonstration on page 437:

Raise the ball at one end of the row a distance of, say, 2 in. and the ball at the other end a distance of 4 in. Then drop both balls simultaneously against the row. The two opposite motions will pass through each other in the row altogether without modification, the larger motion appearing at the end opposite to that at which it started, and the smaller likewise.

Another and more complete analogy to the condition existing within the tube of Fig. 406 may be had by simply vibrating one end of a 2-meter or 3-meter rope, as in Fig. 408. The trains of advancing and reflected waves which continuously travel through one another up and down the rope will unite so as to form a series of nodes and loops. The nodes at c and e are the points at which the advancing and reflected waves are always urging the cord equally in opposite directions. The distance between them is one half the wave length of the train sent down the rope by the hand.

FIG. 408. Nodes and loops in a cord

Summary. The length of the shortest resonant closed pipe is one-fourth wave length. (There is also resonance at any odd multiple of this length.)

The length of the shortest resonant open pipe is one-half wave length. (There is also resonance at any multiple of this length.)

Musical beats are caused by the alternate reinforcement and interference of two sets of wave trains differing in wave length, the number of beats per second being the difference in the two frequencies.

QUESTIONS AND PROBLEMS

A

1. Explain how a piano-tuner uses the phenomenon of beats in tuning a piano.

2. State clearly the meaning of resonance and the meaning of forced vibration, and point out the difference between them.

3. Explain the roaring sound heard when a sea shell, a tumbler, or an empty tin can is held to the ear.

4. What change, if any, is produced in the tone of an organ pipe by a rise in temperature? Give a reason for your answer.

5. Four seconds after a cannon was fired an echo of the report was heard from a distant iceberg. At what distance from the cannon was the iceberg, the temperature being 0° C.?

6. Two tuning forks, one of which has a frequency of 256 per second, emit 5 beats per second when sounded simultaneously. What are the possible rates of vibration of the other fork?

B

1. A gunner hears an echo $5\frac{1}{2}$ sec after he fires. How far away was the reflecting surface, the temperature of the air being 20° C.?

2. (*a*) Account for the sound produced by blowing across the mouth of an empty bottle. (*b*) The bottle may be tuned to different pitches by adding more or less water. Explain.

3. What is the length of the shortest closed tube that will act as a resonator to a fork whose rate is 427 per second? (Temperature = 20° C.)

4. The shortest closed air column that gave resonance with a tuning fork was 32 cm. Find the rate of the fork if the speed of sound was 340 m/sec.

5. Find the number of vibrations per second of a fork which produces resonance (*a*) in a closed pipe 1 ft long; (*b*) in an open pipe 1 ft long. (Take the speed of sound as 1130 ft/sec.)

6. A standard tuning fork of frequency 256 gives 4 beats per second when sounded with another fork. When a piece of wax is attached to the standard fork the number of beats is reduced to 3 per second. What is the frequency of the other fork?

7. The sound of a tuning fork is reinforced when held over a closed air column 4 in. long, and the next position of resonance occurs

when the air column is 12 in. long. Find the frequency of the fork, the temperature being 20° C.

8. A man riding on an express train moving at the rate of 1 mi/min hears a bell ringing in a tower in front of him. (*a*) If the bell makes 280 vibrations per second, how many pulses will strike his ear per second, the velocity of sound being 1120 ft/sec? (The number of extra impulses received per second by the ear is equal to the number of wave lengths contained in the distance traveled per second by the train.) (*b*) What effect has this upon the pitch? (*c*) Had he been going from the bell at this rate, how many pulses per second would have reached his ear? (*d*) How would this affect the pitch?

9. A sound produced at the bottom of a ship comes back to the ear from the bottom of the water in 5 sec. How deep is the water? (See page 436.)

CHAPTER XVII

Properties of Musical Sounds

Musical Scales

Physical basis of musical intervals. Anyone who has heard music knows that there are some combinations of sounds that are pleasing and some that are not. This was discovered early in history. The physical basis for the combination of sounds we call harmony is nicely brought out by the following experiment:

Bore four concentric rows of equidistant holes in a metal or cardboard disk 10 or 12 in. in diameter, the successive rows containing respectively 24, 30, 36, and 48 holes (Fig. 409). The holes should be about $\frac{1}{4}$ in. in diameter, and the rows should be about $\frac{1}{2}$ in. apart. Place this disk (a siren) in the rotating apparatus and whirl it at a constant speed. Then direct a jet of air, as in the demonstration on page 443, against each row of holes in succession. It will be found that the musical sequence *do, mi, sol, do′* results. If the speed of rotation is increased, each note will rise in pitch, but the sequence will remain unchanged.

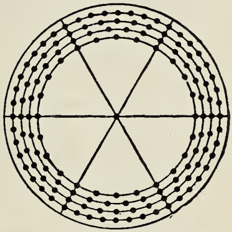


FIG. 409. Siren for producing musical sequence *do, mi, sol, do′*

We learn, therefore, that *the musical sequence do, mi, sol, do′ consists of notes whose vibration numbers have the ratios of 24, 30, 36, 48, that is, 4, 5, 6, 8, and that this sequence is independent of the absolute vibration numbers of the tones.*

Furthermore, when two notes an octave apart are sounded together, they form the most harmonious combination which it is possible to obtain. This characteristic of notes an octave apart was recognized in the earliest times, long before

anything whatever was known about the ratio of their vibration numbers. The preceding experiment showed that *this ratio is the simplest possible,* namely, 24 to 48, or 1 to 2. Again, the next easiest musical interval to produce, and the next most harmonious combination which can be found, corresponds to the two notes commonly designated as *do, sol.* Our experiment showed that this interval corresponds to the next simplest possible vibration ratio, namely, 24 to 36, or 2 to 3. When *sol* is sounded with *do′*, the vibration ratio is seen to be 36 to 48, or 3 to 4. We see, therefore, that the three simplest possible ratios of vibration numbers, namely, 1 to 2, 2 to 3, and 3 to 4, are used in the production of the three notes *do, sol, do′*. Again, our experiment shows that another harmonious musical interval, *do, mi,* corresponds to the vibration ratio 24 to 30, or 4 to 5. We learn, therefore, that *harmonious musical intervals correspond to very simple vibration ratios.*

The major diatonic scale. When the three notes *do, mi, sol,* which, as seen above, have the vibration ratios 4, 5, 6, are all sounded together, they form a remarkably pleasing combination of tones. This combination was picked out and used very early in the musical development of the race. It is now known as the *major chord. The major diatonic scale is built up of three major chords* in the manner shown in the following table, where the first major chord is denoted by *1,* the second by *2,* and the third by *3*:

Syllables	*do*	*re*	*mi*	*fa*	*sol*	*la*	*ti*	*do′*	*re′*
Letters	C	D	E	F	G	A	B	C′	D′
Vibration ratios . . .	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2	$\frac{9}{4}$
	1		*1*		*1*				
					2		*2*		*2*
				3		*3*		*3*	

The chords *do-mi-sol* (the tonic), *sol-ti-re′* (the dominant), and *fa-la-do′* (the subdominant) occur frequently in all music.

Middle-C forks for physical laboratories have the vibration number 256, which makes A $426\frac{2}{3}$. In the so-called *international pitch* A has 435 vibrations, and in the widely adopted American Federation of Musicians pitch, 440.

The even-tempered scale. If G is taken as *do*, and a scale built up with the same vibration ratios as above, it will be found that six of the notes in each octave in the table above can be used in this new key, but that two additional ones are required. (See table below.) Similarly to build up scales, as above, in all the keys demanded by modern music would require about fifty notes in each octave. So, to compromise, the octave is divided into twelve equal intervals represented by the eight white and five black keys of a piano. How this so-called *even-tempered scale* differs from the ideal, or diatonic, scale is shown below.

	C	D	E	F	G	A	B	C′	D′	E′	F′	G′
Diatonic . .	256	288	320	$341\frac{1}{3}$	384	$426\frac{2}{3}$	480	512	576	640	682.2	768
Diatonic key of G					384	*432*	480	512	576	640	*720*	768
Tempered . .	256	287.4	322.7	341.7	383.8	430.7	483.5	512	574.8	645.4	683.4	767.6

Violinists sometimes play better music by using the ideal scale, although in general only a trained ear can tell the difference between the two.

*Vibrating Strings**

Laws of vibrating strings. Stretch two piano wires over a box or a board with pulleys attached so as to form a *sonometer* (Fig. 410). Adjust the weights *A* and *B* until the two wires emit exactly the same note. The phenomenon of beats will make it possible to do this with great accuracy. Then insert the bridge *D* exactly at the middle of one of the wires and pluck the two wires in succession. The interval will be recognized at once as *do*,

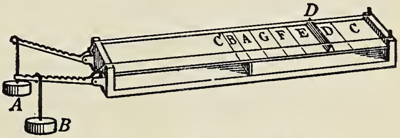


Fig. 410. The sonometer

* This discussion should be followed by a laboratory experiment on the laws of vibrating strings. See, for example, Experiment 53 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis.

do′. Next insert the bridge so as to make one wire two thirds as long as the other and pluck the two again. The interval will be recognized as *do, sol*.

Now it was shown on page 457 that *do′* has twice as many vibrations per second as *do*, and *sol* has three halves as many. Hence, since the length corresponding to *do′* is one half as great as the first length, and that corresponding to *sol* two thirds as great, we conclude from this experiment that, other things being equal, *the vibration numbers of strings are inversely proportional to their lengths.*

Again, tune the two wires to unison and then increase the weight *A* until the pull which it exerts on the wire is exactly four times as great as that exerted by *B*. The note given out by the *A* wire will again be found to be an octave above that given out by the *B* wire.

We learn, then, that *the vibration numbers of similar strings of equal length are proportional to the square roots of their tensions.*

By similar experiments with wires of different mass per unit length we learn that *the vibration numbers of strings are inversely proportional to the square root of the mass per unit length, other things being equal.*

All three of these relations are used in the piano. The strings for the lower notes are longer, thicker, and less tightly stretched than those for the higher notes. The strings for the very low notes are wrapped with fine wire to increase their weight.

Nodes and loops in vibrating strings. Attach a string 1 m long to one of the prongs of a large tuning fork which makes about 100 vibrations per second. Attach the other end as in the figure and set the fork into vibration. If the fork is not electrically driven, which is much to be preferred, it may be bowed with a violin bow or struck with a soft mallet. By making the tension of the thread, for example, proportional to the numbers 9, 4, and 1 it will be found possible to make it vibrate either as a whole (Fig. 411), or in two or three parts (Fig. 412).

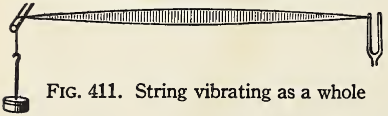


FIG. 411. String vibrating as a whole

This effect is due, as explained on page 453, to the interference of the direct and reflected waves sent down the string from the vibrating fork. Two waves going in opposite directions give the effect of a single wave vibrating in place. As we will show in the next section, we may for all practical purposes think of the string as clamped at each node, and as actually vibrating in two or three or four separate parts, as the case may be.

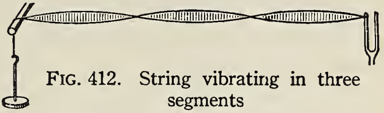


FIG. 412. String vibrating in three segments

Summary. **Harmonious musical intervals correspond to simple vibration ratios, the octave being 1 to 2.**

A major chord consists of the vibration ratios 4, 5, 6.

The major diatonic scale is built up of three major chords.

The frequencies of similar strings are inversely as their lengths, directly as the square roots of their tensions, and inversely as the square roots of their weights per unit length.

QUESTIONS AND PROBLEMS

A

1. A certain tuning fork has a vibration frequency of 512. What is the frequency of a tuning fork whose pitch is (*a*) one octave lower? (*b*) one octave higher?

2. A man singing in a room at temperature 20° C. sends out a wave 9 ft long. What is the pitch (frequency) of the note sounded?

3. Find the wave length of the lowest note on the piano ($A_4 = 27.2$); the wave length of the highest note ($C'''' = 4137$). (Take the speed of sound as 1130 ft per second.)

4. In what three ways do piano-makers obtain the different pitches?

5. A wire 50 cm long gives out 400 vibrations per second. How many vibrations will it give when the length is reduced to 10 cm?

6. At what point must the G_1 string be pressed by the finger of the violinist in order to produce the note C? (Subscripts denote the octaves below middle C, primes the octaves above it.)

B

1. Build up a diatonic scale on C = 264.

2. If middle C had 300 vibrations per second, how many vibrations would F and A have?

3. What is the wave length of international A when the speed of sound is 1131 ft/sec?

4. A wire gives out the note C when the tension on it is 4 kg. What tension will be required to give out the note G?

5. If one wire has twice the length of another and is stretched by four times the stretching force, how will their vibration numbers compare?

6. What is the pitch of a note whose wave length is 5.4 in., the speed being 1152 ft/sec?

7. Two strings, each 6 ft long, make 256 vibrations per second. If one of the strings is lengthened 1 in., how many beats per second will be heard?

8. If a vibrating string is found to produce the note C when stretched by a force of 10 lb, what must be the force exerted to cause it to produce (*a*) the note E? (*b*) the note A?

Fundamentals and Overtones

Fundamentals and overtones. On page 461 we stated that a string which has a node in the middle may be considered as clamped at the node and vibrating in two sections. If this is true, a string vibrating in this way should communicate to the air twice as many pulses per second as the same string vibrating as a whole. This may be conclusively tested as follows:

Pluck the sonometer wire in the middle and note carefully the pitch of the corresponding tone. Then touch the finger to the middle of the wire and pluck the latter midway between this point and the end.* The octave of the original note will be distinctly heard. Next touch the finger at a point one third of the wire length from one end and again pluck the wire. The note will be recognized as *sol′*. Since we learned on page 457 that *sol′* has three halves as many vibrations

*It is well to remove the finger almost simultaneously with the plucking.

as *do'*, it must have three times as many vibrations as the original note, *do*. Hence a wire which is vibrating in three segments sends out three times as many vibrations as when it is vibrating as a whole.

When a wire vibrates simply as a whole, it gives forth the lowest note which it can produce. This note is called the *fundamental*, or first partial, of the wire. When the wire is made to vibrate in two parts, it gives forth, as has just been shown, a note an octave higher than the fundamental. This is called the *first overtone*, or second partial. When the wire is made to vibrate in three parts, it gives forth a note corresponding to three times the vibration number of the fundamental, namely, *sol'*. This is called the *second overtone*, or third partial. When the wire vibrates in four parts, it gives forth the third overtone, which is two octaves above the fundamental. The partials of wires are often called *harmonics*. They bear the vibration ratios 2, 3, 4, 5, 6, 7, etc. to the fundamental.*

Simultaneous production of fundamentals and overtones. Thus far we have produced overtones only by forcing the wire to remain at rest at certain points during the bowing.

Now pluck the wire at a point one fourth of its length from one end, *without touching it in the middle*. The tone most distinctly heard will be the fundamental; but if the wire is now touched very lightly exactly in the middle, the sound, instead of ceasing altogether, will continue, but the note heard will be an octave higher than the fundamental, showing that in this case there was also superposed upon the vibration of the wire as a whole a vibration in two segments (Fig. 413).

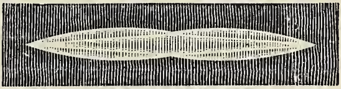


FIG. 413. A wire simultaneously emitting its fundamental and first overtone

By touching the wire in the middle the vibration as a whole was destroyed, but that in two parts remained. Repeat the experiment with this difference, that the wire is now plucked in the middle instead of one fourth its length from one end. If it is now touched

* Some instruments, such as bells, can produce higher tones whose vibration numbers are not exact multiples of the fundamental. These notes are still called overtones, but they are not called harmonics, the latter term being reserved for the multiples. Strings produce harmonics only.

in the middle, the sound will cease entirely, showing that when a wire is plucked in the middle, there is no first overtone superposed upon the fundamental. Pluck the wire again one fourth of its length from one end and give careful attention to the compound note emitted. It will be found possible to recognize both the fundamental and the first overtone sounding at the same time. Similarly, by plucking at a point one sixth of the length of the wire from one end, and then touching it at a point one third of its length from the end, the second overtone may be made to appear distinctly, and a trained ear will detect it in the note given off by the wire, even before the fundamental is suppressed by touching at the point indicated.

The experiments show that in general *the note emitted by a string plucked at random is a complex one, consisting of a fundamental and several overtones, and that just what overtones are present in a given case depends on where and how the wire is plucked.*

Quality. Pluck the sonometer wire first in the middle and then close to one end. The two notes emitted will have exactly the same pitch, and they may have exactly the same loudness, but they will be easily recognized as different with respect to something which we call *quality*. The experiment of the last section shows that the real physical difference in the tones is a difference in the sorts of overtones which are mixed with the fundamental in the two cases.

Sound a mounted C′ fork simultaneously with a mounted C fork. The resultant tone will sound like a rich, full C, changing to a hollow C when the C′ is quenched with the hand.

Everyone is familiar with the fact that when notes of the *same* pitch and loudness are sounded upon a piano, a violin, and a cornet, the three tones can be readily distinguished. The last experiments suggest that the cause of this difference lies in the fact that it is only the *fundamental* which is the same in the three cases, and that the *overtones* are different. In other words, the characteristic of a tone which we call its quality is determined simply by *the number and prominence of the overtones which are present.* If the overtones present are few and weak, and the fundamental is strong, the tone is, as a rule, soft and mellow, as when a flute is played, or a sonometer wire is plucked in the middle, or a closed organ pipe is

blown gently, or a tuning fork is struck with a soft mallet. The presence of comparatively strong overtones up to the fifth adds fullness and richness to the tone.

Analysis of tones by the manometric flame. If in front of the trumpet *G* of the apparatus shown opposite page 442 we hold the open ends of the resonance boxes of two tuning forks, C and C′, and simultaneously sound the forks, the image of the flame will be as shown at the top of Fig. 414. Here we see a complex wave form caused by a combination of two simple tones, one the octave of the other. Any note producing this wave form is therefore known to consist of the fundamental with its first overtone only.

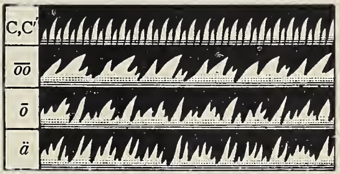


FIG. 414. Analysis of sounds with manometric flames

The proof that most tones are complex lies in the fact that when analyzed by the manometric flame they show figures not like those opposite page 442, which correspond to simple tones, but like those of Fig. 414, which may be produced by sounding combinations of simple tones. The last three wave forms were produced by singing the vowel sounds $\bar{o}\bar{o}$, $\bar{o}$, and $\ddot{a}$ at the same pitch. The beautiful photographs opposite page 467, taken by Professor D. C. Miller, show the extraordinary complexity of spoken words.

Helmholtz's experiment. If the loud pedal on a piano is held down and the vowel sounds $\bar{o}\bar{o}$, $\bar{\imath}$, $\bar{a}$, $\ddot{a}$, $\bar{e}$, are sung loudly into the strings, these vowels will be caught up and returned by the instrument with sufficient fidelity to make the effect almost uncanny.

It was by a method which may be considered as merely a refinement of this experiment that Helmholtz proved conclusively that quality is determined simply by the number and prominence of the overtones which are blended with the fundamental. He first constructed a large number of resonators, like those shown in Fig. 415, each of which would

respond to a note of some particular pitch. By holding these resonators in succession to his ear while a musical note was

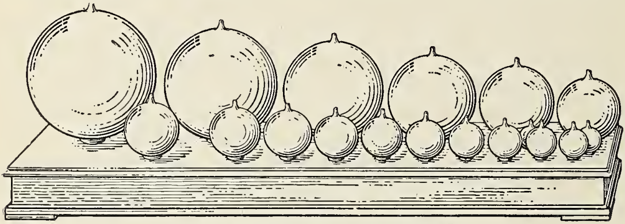


FIG. 415. Helmholtz resonators

sounding, he picked out the constituents of the note; that is, he found out just what overtones were present and what were their relative intensities. Then he put these constituents together and reproduced the original tone. This was done by sounding simultaneously, with appropriate loudness, two or more of a whole series of tuning forks which had the vibration ratios 1, 2, 3, 4, 5, 6, 7. In this way he succeeded not only in imitating the qualities of various musical instruments but even in reproducing the different vowel sounds.

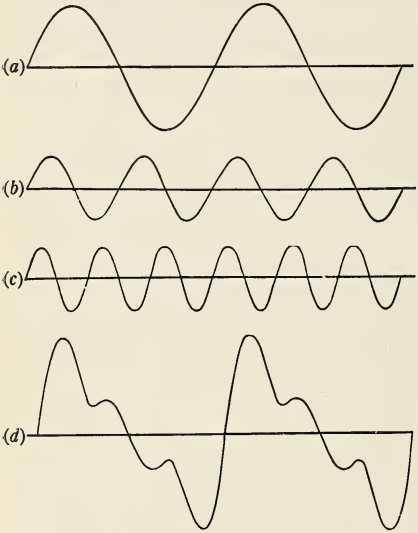
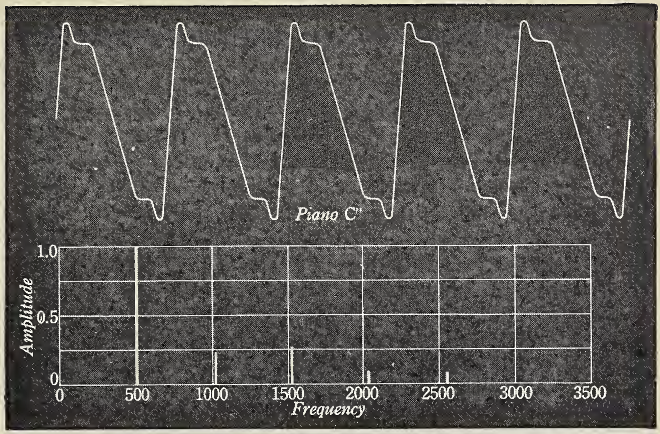
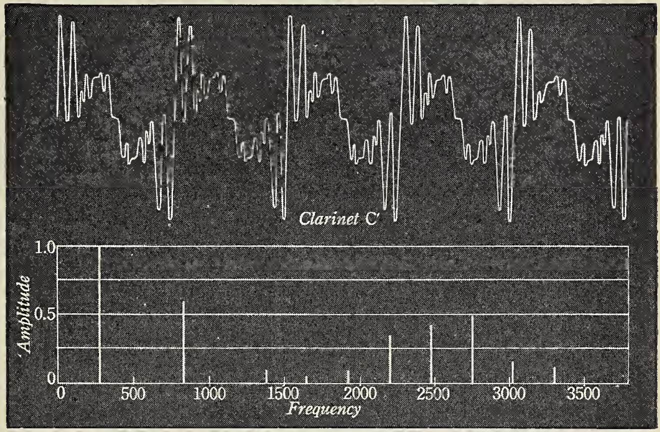


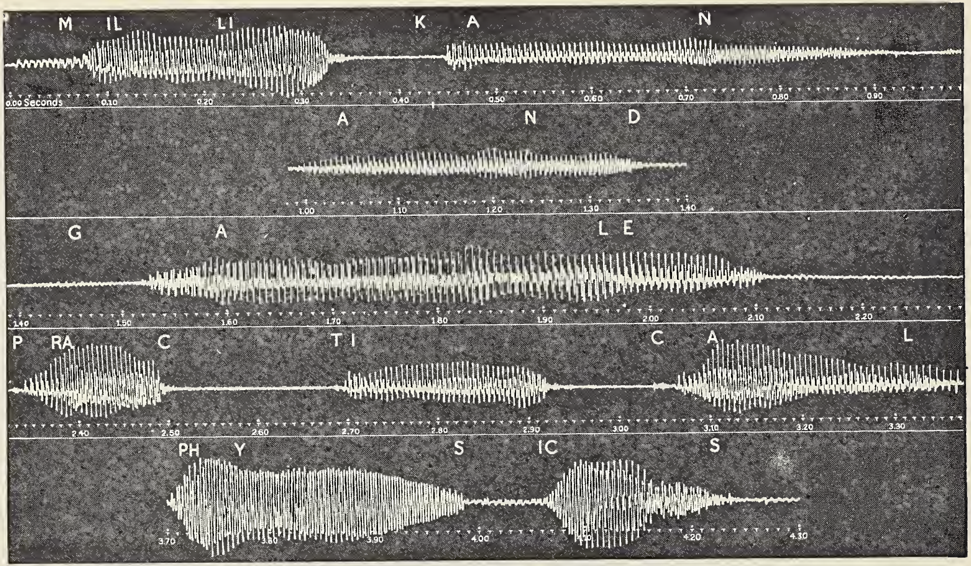
FIG. 416. Diagram showing the combination of pure tones into a complex wave form

In Fig. 416 the fundamental (*a*) and the first two overtones (*b*) and (*c*) are





These Diagrams Show Fletcher's Experimental Analysis of the Component Frequencies



Sound Waves of Spoken Words

The words were spoken at a pitch of from 150 to 180. Waves cause vibrations in a diaphragm which are transferred to a mirror that reflects a beam of light to a moving film. (From a photograph by Professor D. C. Miller)

combined by drawing (*d*) so that it is the sum of (*a*), (*b*), and (*c*). The top line of Fig. 417 is a photographic reproduction of the waves given out by a flute when blown softly. It resembles Fig. 416 (*d*) very closely. When, however, the flute is blown more strongly, the note becomes nearly a pure tone, as shown by the bottom line of Fig. 417. This resembles Fig. 416 (*a*).

By analyzing the notes of different instruments by a method which is the modern equivalent of the Helmholtz method, the characteristic distribution and intensity of overtones have been obtained. (See opposite page 466.) It will

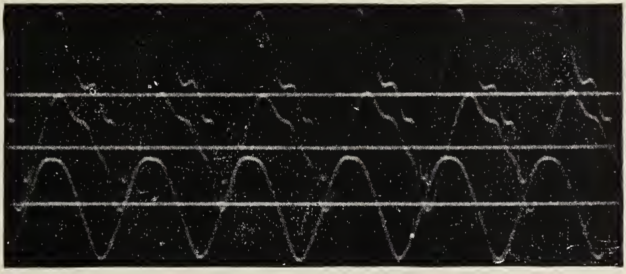


FIG. 417. Photographs of the tones of a flute, played *p*, *mf*, and *f* *

be seen that the quality of the piano C note is largely determined by the first three harmonics (that is, the fundamental and the first and second overtones), whereas the characteristic quality of the clarinet C′ is imposed by the great prominence of the eighth, ninth, and tenth partials, or harmonics.

Sympathetic vibrations. Place two mounted tuning forks of the same pitch with the open ends of their resonators facing each other. Set one into vigorous vibration with a soft mallet and then quickly quench it by grasping the prongs with the hand. The other fork will be found to be sounding loudly enough to be heard over a large room. Next wax a penny to one prong of the second fork and repeat the experiment. When the sound of the first fork is quenched, no sound whatever will be found to be coming from the second fork.

* From *The Science of Musical Sounds*, by Dayton Clarence Miller. Courtesy of The Macmillan Company, publishers.

The experiment illustrates the phenomenon of *sympathetic vibrations* and shows under what conditions it occurs. If two bodies capable of emitting musical notes have exactly the same natural period of vibration, the pulses communicated to the air when one alone is sounding beat upon the second at intervals which correspond exactly to its own natural period. Each pulse, therefore, adds its effect to that of the preceding pulses; and though the effect from a single pulse is very slight, a great number of such pulses produce a large resultant effect. In the same way a large number of very feeble pulls may set a heavy swing into vibration if the pulls come at intervals exactly equal to the natural period of the swing. But if the two sounding bodies have even a slight difference of period, the effect of the first pulses is neutralized by the effect of succeeding pulses as soon as the two bodies, on account of their difference in period, get to swinging in opposite directions.

FIG. 418. Illustrating the production of discords

Sing notes of different pitches into a piano when the dampers are lifted. The wire which has the pitch of the note sounded will in every case respond. Sing a little off the key and the response will cease.

Physical significance of harmony and of discord. Support vertically two pieces of glass tubing about 1 in. in diameter and $1\frac{1}{2}$ ft long, as shown in Fig. 418. Thrust two gas jets (made by drawing down pieces of $\frac{1}{4}$-in. glass tubing until, with full gas pressure, the flame is about 1 in. long) inside these tubes to a height of about 3 or 4 in. from the bottom. Turn the gas down until the tubes begin to "sing." Without attempting to discuss the part which the flame plays in the production of the sound, we wish simply to call attention to the fact that the two tones are either quite in unison or so near it that only a few beats are produced per second. Now increase the length of one of the tubes slightly by slipping the paper cylinder S up over its end. The number of beats will be rapidly increased until they will become indistinguishable as separate beats and will merge into a jarring, grating discord.

The experiment teaches that *discord is simply a phenomenon of beats.* If the vibration numbers do not differ by more than five or six, that is, if there are not more than five or six beats per second, the effect is not particularly unpleasant. From this point on, however, as the difference in the vibration numbers, and therefore in the number of beats per second, increases, the unpleasantness increases, and becomes worst at a difference of about thirty. Thus, the notes B and C′, which differ by about thirty-two beats per second, produce about the worst possible discord. When the vibration numbers differ by as much as seventy, which is about the difference between C and E, the effect is again pleasing, or harmonious. Moreover, in order that two notes may harmonize well, it is necessary not only that the notes themselves shall not produce an unpleasant number of beats, but also that such beats shall not arise from their overtones. Thus, C and B are very discordant, although they differ by a large number of vibrations per second. The discord in this case arises between B and C′, the first overtone of C.

Again, there are certain classes of instruments, of which bells are a striking example, which produce insufferable discords when even such notes as *do*, *sol*, *do′*, are sounded simultaneously upon them. This is because these instruments, unlike strings and pipes, have overtones which are not harmonics, that is, which are not multiples of the fundamental; and these overtones produce beats either among themselves or with one of the fundamentals. It is for this reason that in playing chimes the bells are struck in succession, not simultaneously.

Summary. **The quality of a tone is determined by the number and prominence of the overtones.**

Sympathetic vibrations are possible only when the natural periods of vibration of the two bodies are exactly the same.

Discords are caused by rapid beats.

QUESTIONS AND PROBLEMS

A

1. A violin string is commonly bowed about one seventh of its length from one end. Why is this better than bowing in the middle?

2. What did Helmholtz prove by means of his resonators?

3. A wire gives out the note G. What is its fourth overtone?

4. What is (*a*) the fourth overtone of C? (*b*) the fifth overtone?

B

1. It is forbidden to sound certain low notes on the pipe organs of some of the cathedrals of Europe for fear of ruining one or more of the great stained-glass windows. Explain.

2. Three tuning forks give 256, 288, and 512 vibrations per second respectively. (*a*) Which two of these forks when sounded simultaneously will give the most pleasing effect? (*b*) Which two will give the most unpleasant discord? Explain.

Wind Instruments

Fundamentals of closed pipes. Insert a tightly fitting rubber stopper in a glass tube *a* (Fig. 419), 8 or 10 in. long and about $\frac{3}{4}$ in. in diameter. Push the stopper along the tube until, when a vibrating C′ fork is held before the mouth, resonance is obtained as in the experiment described on page 447. (The length will be 6 or 7 in.) Then remove the fork and blow a stream of air across the mouth of the tube through a piece of tubing *b*, flattened at one end as in the figure.* The pipe will be found to emit strongly the note of the fork.

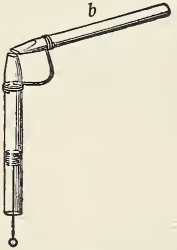
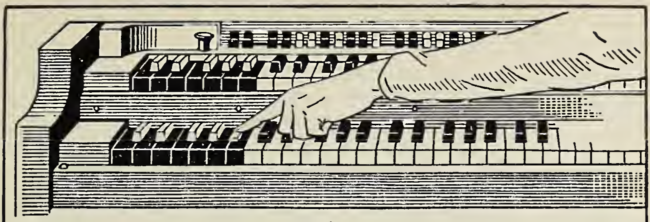


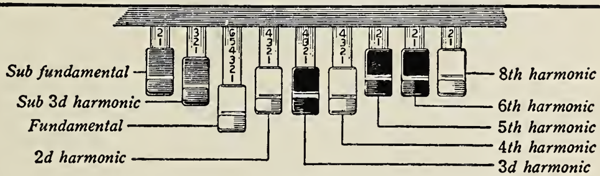
Fig. 419. Musical notes from pipes

In every case it is found that a note which a pipe may be made to emit is always a note to which it is able to respond when used as a resonator. Since

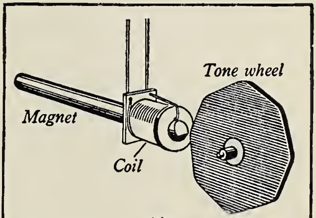
* If the arrangement of Fig. 419 is not at hand, simply blow with the lips across the edge of a piece of ordinary glass tubing within which a rubber stopper may be pushed back and forth



(a)



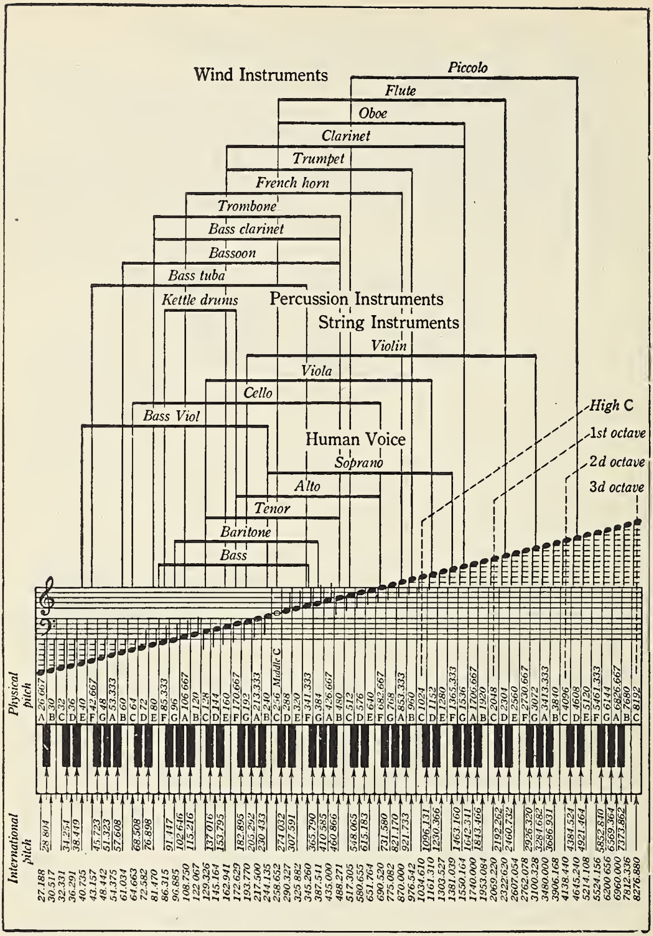
(b)



(c)

This organ does not directly produce any sound at all. It creates music by generating and mixing *electrically* the fundamental frequencies and overtones into which pipe-organ tones have previously been analyzed. The electrical wave form resulting from this mixing is then sent through an ordinary loud-speaker (see page 478) and there transformed into the pipe-organ tones of already known composition. Each of these simple alternating currents of a given frequency is produced by continuously rotating a metallic disk, or tone wheel (*c*), before a permanent magnet surrounded by a coil. There are ninety-one of these gear-driven, continuously rotating tone-generators, the frequency resulting from each depending upon its speed and the number of projections on its edge. Pressing the white keys merely closes the proper electric circuit. The eighteen preset black keys (*a*) perform the same function as the piston buttons on a standard pipe organ; that is, they put at the player's disposal the usual group of organ tone colors. But in addition, by drawing out the stops suitable amounts (*b*), the player is able to change *at will* the number and intensity of the harmonics used and thus to create an endless variety of new tone colors. The instrument is run off the ordinary house-lighting circuit and can never be out of tune

The Hammond Organ



Acoustic Frequency Reference Chart

Courtesy of the Electrical Research Products Company

the best resonance was found (p. 448) when the wave length given out by the fork was four times the length of the pipe, we learn that *when a current of air is suitably directed across the mouth of a closed pipe, it will emit a note which has a wave length four times the length of the pipe.* This note is called the *fundamental* of the pipe. It is the lowest note which the pipe can be made to produce.

Fundamentals of open pipes. Since we found (p. 449) that the lowest note to which a pipe open at the lower end can respond is one the wave length of which is twice the pipe length, we infer that an open pipe, when suitably blown, ought to *emit* a note the wave length of which is twice the pipe length. This means that if the same pipe is blown first when closed at the lower end and then when open, the first note ought to be an octave lower than the second.

Close the pipe *a* (Fig. 419) at the bottom with the hand and blow across it; then remove the hand and repeat the operation. The second note will indeed be found to be an octave higher than the first.

We learn, therefore, that *the fundamental of an open pipe has a wave length equal to twice the pipe length.*

Overtones in pipes. It was found (p. 449) that there is a whole series of pipe lengths which respond to a given fork, and that these lengths bear to the wave length of the fork the ratios $\frac{1}{4}$, $\frac{3}{4}$, $\frac{5}{4}$, etc. This is equivalent to saying that a closed pipe of *fixed* length can respond to a whole series of notes whose vibration numbers have the ratios 1, 3, 5, 7, etc. Similarly we found (p. 449) that in the case of an open pipe the series of pipe lengths which will respond to a given fork bear to the wave length of the fork the ratios $\frac{1}{2}$, $\frac{2}{2}$, $\frac{3}{2}$, $\frac{4}{2}$, etc. This, again, is equivalent to saying that an open pipe can respond to a series of notes whose vibration numbers have the ratios 1, 2, 3, 4, 5, etc. Hence we infer that it ought to be possible to cause both open and closed pipes to emit notes of higher pitch than their fundamentals (that is, overtones), and that the first overtone of an *open* pipe should have twice the rate of vibration of the fundamental (that is, it should be

do′, the fundamental being considered as *do*); that the second overtone should vibrate three times as fast as the fundamental (that is, it should be *sol′*); that the third overtone should vibrate four times as fast (that is, it should be *do″*); that the fourth overtone should vibrate five times as fast (that is, it should be *mi″*); etc. In the case of the *closed* pipe, however, the first overtone should have a vibration rate three times that of the fundamental (that is, it should be *sol′*); the second overtone should vibrate five times as fast (that is, it should be *mi″*); etc. In other words, while an open pipe ought to give forth *all* the harmonics, both odd and even, a closed pipe ought to produce the *odd* harmonics but be entirely incapable of producing the *even* ones.

Blow the pipe of Fig. 419 so as to produce the fundamental when the lower end is open. Then increase the strength of the air blast. The note will be found to spring to *do′*. By blowing still harder it will spring to *sol′*, and a still further increase will probably bring out *do″*. The odd and the even harmonics are, in fact, emitted by the open pipe, as our theory predicted. When the lower end is closed, however, the first overtone will be found to be *sol′* and the next one *mi″*, just as our theory demands for the closed pipe.

[**Mechanism of emission of notes by pipes.** Blowing across the mouth of a pipe produces a musical note because the jet of air vibrates back and forth across the lip in a period which is determined wholly by the natural resonance period of the pipe. Thus, suppose that the jet *a* (Fig. 420) first strikes just inside the edge, or *lip*, of the pipe. A condensational pulse starts down the pipe. When it returns to the mouth after reflection at the closed end, it pushes the jet outside the lip. This starts a rarefaction down the pipe, which, after return from the lower end, pulls the jet in again. There are thus sent out into the room regularly timed puffs, the period of which is controlled by the reflected pulses coming back from the lower end, that is, by the natural resonance period of the pipe.

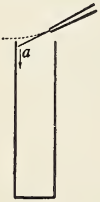


FIG. 420. Vibrating air jet

[By blowing more violently it is possible to create, by virtue of the friction of the walls, so great and so sudden a compression in the mouth of the pipe that the jet is forced out over the edge before the return of the first reflected pulse. In this case no note will be produced unless the blowing is of just the right intensity to cause the jet to swing out in the period corresponding to an overtone. In this case the reflected pulses will return from the end at just the right intervals to keep the jet swinging in this period. This shows why a current of a particular intensity is required to start any particular overtone.

FIG. 421. Organ pipe

[Another way of looking at the matter is to think of the pipe as being filled up with air until the pressure within it is great enough to force the jet outside the lip, upon which a period of discharge follows, to be succeeded in turn by another period of charge. These periods are controlled by the length of the pipe and the violence of the blowing, precisely as described above.

[With open pipes the situation is in no way different except that the reflection of a condensation as a rarefaction at the lower end makes the natural period twice as high, since the pipe length is now one-half wave length instead of one-fourth wave length (p. 449).

[**Vibrating-air-jet instruments.** The mechanism of the production of musical tones by the ordinary organ pipe (Fig. 421), the flute (Fig. 422), the fife, the piccolo, and all whistles

FIG. 422. The flute: a vibrating-air-jet instrument

is essentially the same as in the case of the pipe of Fig. 420. In all these instruments an air jet is made to play across the edge of an opening in an air chamber, and the reflected pulses returning from the other end of the chamber cause it to

vibrate back and forth, first into the chamber and then out again. In this way a series of regularly timed puffs of air is made to pass from the instrument to the ear of the observer precisely as in the case of the rotating disk (p. 442). The air chamber may be either open or closed at the remote end. In the flute it is open, in whistles it is usually closed, and in organ pipes it may be either open or closed. Fig. 421 shows a cross section of an organ pipe. The jet of air from S vibrates across the lip L in obedience to the pressure exerted on it by waves reflected from O. Pipe organs are provided with a

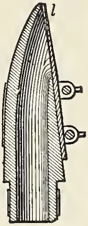


FIG. 423. Mouthpiece of a clarinet, showing the tongue l, which opens and closes the upper end of the pipe

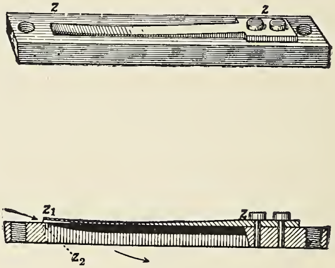


FIG. 424. The vibrating tongue of the mouth organ, accordion, etc.

different pipe for each note, but the flute, piccolo, and fife are made to produce a whole series of notes either by blowing overtones or by opening holes in the tube — an operation which is equivalent to cutting the tube off at the hole.

¶ **Vibrating-reed instruments.** In reed instruments the vibrating air jet is replaced by a vibrating reed, or tongue, which opens and closes, at absolutely regular intervals, an opening against which the performer is directing a current of air. In the clarinet (Fig. 426), the oboe, the bassoon, the saxophone, etc. the reed is placed at the upper end of the tube (l, Fig. 423), and the theory of its opening and closing the orifice so as to admit successive puffs of air to the pipe is identical with the theory of the fluctuation of the air jet into and out of the organ pipe. For in these instruments the reed has little

rigidity and its vibrations are controlled largely by the reflected pulses but partly by the reed and by the lips of the performer.

[In other reed instruments, like the mouth organ, the common reed organ, or the accordion, it is the elasticity of the reed alone (z, Fig. 424) which controls the emission of pulses. In such instruments there is no necessity for air chambers. The arrows of Fig. 424 indicate the direction of the air current which is interrupted as the reed vibrates between the positions z_1 and z_2.

FIG. 425. The reed organ-pipe

[In still other reed instruments, like the reed pipes used in large organs (Fig. 425), the period of the pulses is controlled partly by the elasticity of the reed and partly by the return of the reflected waves; in other words, the natural period of the reed is more or less coerced by the period of the reflected pulses. Within certain limits, therefore, such instruments may be tuned by merely changing the length of the vibrating reed l. This is done by pushing the wire r up or down.

FIG. 426. The clarinet: a vibrating-reed instrument

[**Vibrating-lip instruments.** In instruments of the bugle and trumpet (Fig. 427) type the vibrating reed is replaced by the

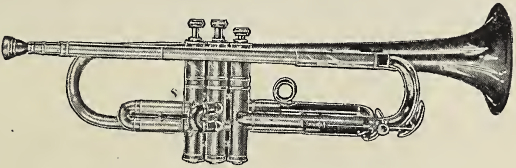


FIG. 427. The trumpet: a vibrating-lip instrument

vibrating lips of the musician, the period of their vibration being controlled, precisely as in the organ pipe or the clarinet, by the period of the returning pulses. In the bugle the pipe length is fixed, the instrument being without keys, and because of the narrowness of the tube all bugle calls are played with overtones.

Sound Reproduction

The phonograph. In the original form of the phonograph the sound waves, collected by the cone, are carried to a thin metallic disk *C* (Fig. 428), exactly like a telephone diaphragm, which takes up very nearly the vibration form of the wave which strikes it. This vibration form is permanently impressed on the wax-coated cylinder *M* by means of a stylus *D* which is attached to the back of the disk. When the stylus is run a second time over the groove which it first made in the wax, it receives again and imparts to the disk the vibration form which first fell upon it. This is the principle of the "Dictaphone" and the "Ediphone," used to replace stenographers in business offices. The typist writes the letter by listening to the reproduction of the dictation.

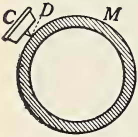


FIG. 428

In so-called hill-and-dale reproduction the vibrations of the needle are, as in the original form, up and down; that is, it is the *depth* of the groove that varies. In most commercial records, however, the needle moves sideways, and a delicate lever translates this sideways wavy line into a back-and-forth motion of the diaphragm (Fig. 429).

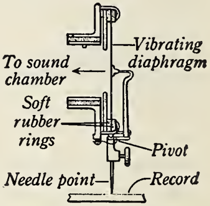
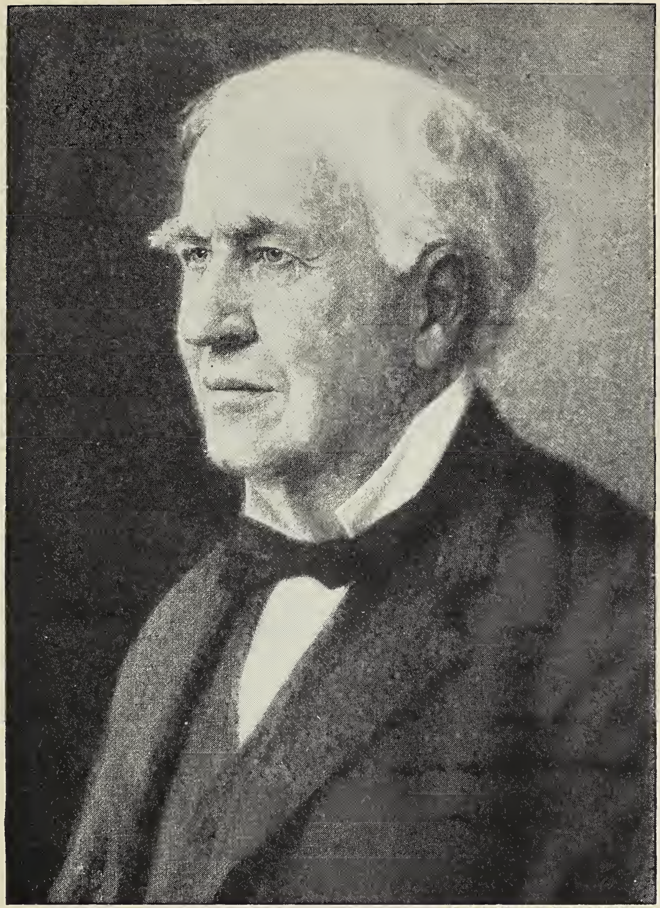


FIG. 429. The lateral-cut record

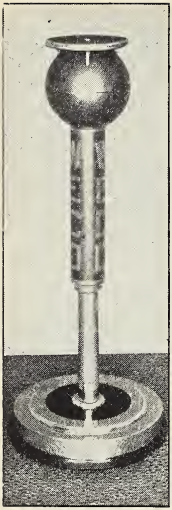
[In the making of a record the wavy trace is first cut in soft wax, from which hard copper electrotypes (p. 341) are made. The wavy trace is then transferred from the copper plate by a



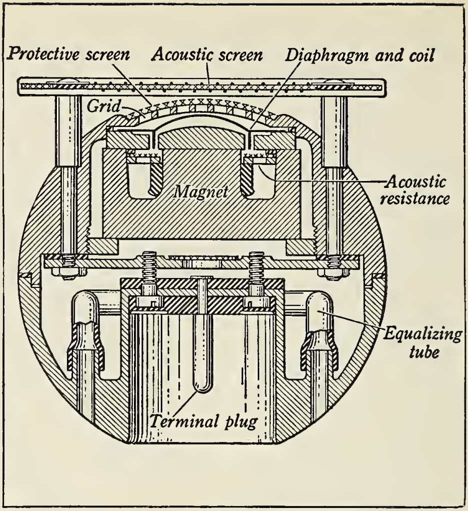
© T.A.E., from Ewing Galloway

Thomas A. Edison (1847–1931)

The greatest and most prolific of all inventors; invented the phonograph, the high-resistance carbon-filament lamp, quadruplex telegraphy, and scores of other things



(a)



(b)

Photograph (a) and Simplified Cross-Section View (b) of a Nondirectional Moving-Coil Microphone

The diaphragm against which the air waves beat (see top of drawing (*b*)) is made of exceedingly thin and light duralumin. It has a dome-shaped central portion which extends to the inner edge of the moving coil. This stiffens the center of the diaphragm to such an extent that it vibrates substantially as a plunger throughout the whole frequency range 35 to 12,000. The moving coil is forced by the air waves beating upon the top of this plunger to cut the magnetic lines of force which the permanent magnet throws across the narrow slot in which the coil vibrates. This generates in the coil alternating currents of the same wave form as the incident air waves that move the diaphragm. These currents are magnified by an amplifier and then sent out to the loud-speaker, to the telephone line, or to the antennae of the radio system. The acoustic resistance, indicated in the drawing, is merely narrow channels through which the air is forced by the vibrations to pass from one of the two large air chambers to the other. This is merely an air-damping device that helps in enabling the movements of the plunger to reproduce perfectly the wave form of the incident sound waves. The nondirectional property is provided by the acoustic screen, which reflects back to the diaphragm waves coming in from below and transmits through its opening waves coming in from above. The equalizing tube is to keep the air pressure the same inside and outside. (Courtesy of the Bell Telephone Laboratories)

hydraulic force of from 5 to 10 tons applied to the commercial disks when they are hot enough to receive the impression.

Since electrical methods have now replaced mechanical ones in all recording and in most reproducing, it will be worth while to study what is involved in these new methods.

The condenser microphone. The carbon-granule type of transmitter, the action of which was explained fully on page 422, although still used in ordinary telephones, reproduces the impressed wave forms too imperfectly for the exacting demands of broadcasting and the sound motion pictures. The great recent development in these arts has been in no small degree due to the development of two new forms of

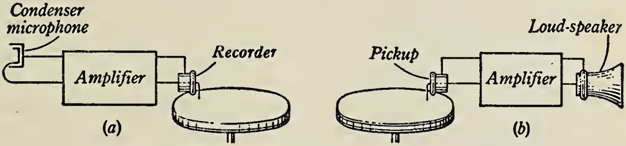


FIG. 430. Electrical recording and reproducing of sound

microphone known as (1) the condenser microphone and (2) the moving-coil microphone.

The condenser microphone (Fig. 430 (*a*)) is in principle merely two insulated parallel plates separated by a cushion of air only one thousandth of an inch thick. The front plate, upon which the air waves fall, consists of a very thin diaphragm. The back-and-forth movements of this diaphragm follow very accurately the form of the impressed sound wave and in so doing continuously change the capacity of the condenser by altering the minute distance between its plates. As this capacity increases, more electricity flows into the condenser from a constant-potential battery, the terminals of which are connected through a very high resistance to the two condenser plates. The varying currents through this high resistance cause exactly corresponding varying potentials at its two ends. This varying voltage is applied to the grid of an electron-tube amplifier (p. 577). This then sends into its

circuit very much larger currents, which, however, reproduce very perfectly the wave form of the incident sound waves. These currents pass through the moving coil of the loud-speaker, which then translates them into amplified sound waves. Fig. 430 (*a*) shows the relations between the microphone, the amplifier, and the recorder in the process of making a phonograph record. Fig. 430 (*b*) shows the corresponding relations in reproducing the record. The recorder and pickup are moving-coil instruments of the type described in the following paragraph.

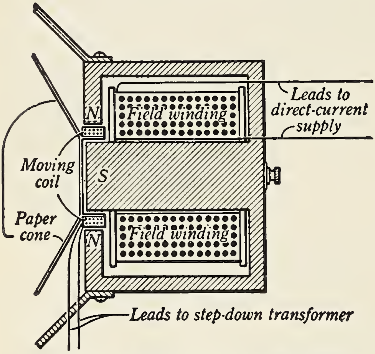


FIG. 431. A section of a loud-speaker

The loud-speaker. In the most approved form of modern loud-speaker the amplified currents from a telephone, phonograph, or radio circuit are led through a very light moving coil of many turns of fine wire lying between the poles *NS* (Fig. 431) of a strong electromagnet. The conducting wires of this coil run at right angles to the lines of force of the magnetic field. Precisely as in the electric motor (see the motor rule, p. 394) the reaction between this magnetic field and the currents flowing through the moving coil exerts on this coil forces proportional to the strength of the current. These forces move the coil in and out so that the paper diaphragm, or cone, attached to it (Fig. 431) sends out exactly the amplified wave form of the air waves that originally struck the microphone. This form of loud-speaker is practically free from any natural frequencies of its own in either the diaphragm or the horn. Because of this quality it reproduces accurately all frequencies from 35 to 12,000 cycles. Sounds which go through a *recording* mechanism, however, stop at about 8000 cycles.

¶**The moving-coil microphone.** This microphone is not different in principle from the loud-speaker save that in the loud-speaker the energy transfer is from electric currents to sound waves, whereas in the microphone it is the reverse. Also, since the microphone must respond to the very feeble air waves involved in ordinary speech instead of to the greatly amplified currents from an electron-tube amplifier, it must be made more sensitive than the loud-speaker. Both a diagram and a photograph of the moving-coil microphone are shown opposite page 477, together with a description of how it works.

¶Of the four types of microphones that have been used, namely, (1) the carbon transmitter (Fig. 379), (2) the vibrating iron disk (Fig. 378), (3) the condenser microphone (Fig. 430), and (4) the moving-coil microphone, the last has now rendered all the others nearly obsolete for high-quality reproduction of all kinds, whether in sound motion pictures, broadcasting, phonograph reproduction, or telephony. The carbon transmitter is still used in ordinary telephones, but even here steps are being taken to replace it with the moving-coil transmitter.

¶The following data convey some idea of how perfectly the moving-coil microphone does its work and how much the world owes to the American scientists and engineers who have been in large measure responsible for solving within the past fifteen years the exceedingly difficult problems involved in creating high-fidelity sound reproduction. To consider but one instrument, in 1919, with the old mechanical phonograph (Fig. 428), in which the sound fell directly on the diaphragm actuating the needle and was reproduced directly from the phonograph record by the reverse process, the whole obtainable frequency range was from 250 to 3000 cycles. In 1936, with the electrical mode of recording and reproducing which has been introduced within this period, the limits set by the moving-coil microphone and the loud-speaker are 35 and 12,000 cycles. Practically all audible frequencies are within these limits. Indeed, although for normal ears the limit of

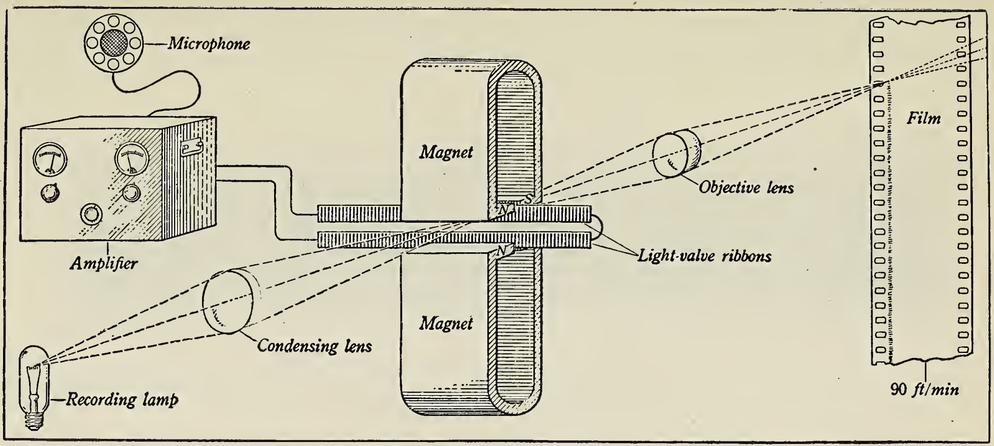
audibility is passed at about 16,000, for "perfect reproduction" of music and speech no frequencies higher than 12,000 are at all significant.

[So far as phonograph reproduction is concerned, the upper limit is set at about 8500 by the imperfections in the trace on the record rather than by the characteristics of the microphone or the loud-speaker.

[When a symphony is transmitted by wire to broadcasting stations, the characteristics of the telephone line impose an upper limit of about 5000 or 6000 cycles. The loss of the higher frequencies above this limit does indeed perceptibly modify the quality, although it is only by listening in quick succession first directly to the orchestra and then to the transmitted music that most people can tell the difference.

Sound motion pictures. For successful sound motion pictures the first requirement is a distortionless microphone (like that just described), which transforms sound waves into amplified electric currents of the same wave form. To get the sound record on the film, by far the most common procedure is to pass these amplified currents through a so-called light valve. This consists of two fine duralumin* ribbons placed edge to edge so that the normal opening between them is a thin slit about one thousandth of an inch wide. These two ribbons are in the field of a powerful electromagnet the lines of force of which run at right angles to the plane of the ribbons. The amplified voice currents from the microphone flow up one of these ribbons and down the other. By the motor rule the field of the magnet pulls these two ribbons apart, thus opening the slit between them by an amount proportional to the strength of the current through the ribbons. Thus the amount of light passing through the slit from a beam directed against the ribbons varies in just the way the voice currents vary. This light of varying intensity from the light valve is directed upon a narrow strip on one side of the film and makes there a sound track on the developed film which

* An alloy of aluminum, copper, manganese, and magnesium, which is nearly as light as aluminum and nearly as strong as soft steel.



The Light Valve and the Variable-Density-Sound-Track System

In this system the light valve is the key to sound motion pictures. The light-valve ribbons have normally only 0.001 inch opening between them. In accordance with the motor rule these two ribbons, when carrying current, are pulled in opposite directions by the magnetic field, so that the changes in the amount of light passing through the valve reflect accurately the fluctuations in the current in the ribbons, and these in turn reflect the wave form of the original sound which went into the microphone. When, in the process of sound reproduction, light is sent back in just the reverse direction through the variable-density sound track and then enters a photoelectric cell (see Chap. XXIII), the currents going from this cell into the loud-speaker are able to reproduce the original sound

Variable-Density Sound Track

The opening and closing of the light valve (see opposite page 480) is reflected in the darkening and lightening of the sound track (see arrow) on the film. (Courtesy of the Electrical Research Products Company)

Variable-Amplitude Sound Track

The photoelectric currents produced by the sounds to be recorded, and having the wave form of these sounds, pass through a very light galvanometer, called an oscillograph. The very narrow ray of light reflected from the tiny mirror of the oscillograph then writes this wave form on the sound track. The reproduction of this sound track is accomplished in precisely the same way as that of the variable-density sound track. (Courtesy of the General Electric Company)

has variations in density corresponding exactly to the variations of the voice currents.

Now consider how the sounds are reproduced from the film. The film is made to pass in front of a slit illuminated by a constant source. The light that comes through this slit after passing through the sound track has variations in intensity corresponding to the variations in the voice currents. This beam of light of varying intensity is directed upon a photoelectric cell (p. 603) which has the property of emitting from the small surface on which the light falls electron currents that are exactly proportional to the light intensity. These currents are then passed through a loud-speaker, which thus sends back into the air exactly the wave form of the sound that originally fell upon the moving-coil microphone.

The foregoing is a description of the making and operation of what is called the *variable-density* sound track, which is used in about 90 per cent of the sound motion pictures. A rival method yields the *variable-width* sound track. It is essentially the method by which the trace opposite page 467 was made. A tiny spot of light falls on the film from a small oscillating mirror attached to a galvanometer (oscillograph) coil so exceedingly free from inertia that its turning movements follow all the variations in the amplified voice currents that are sent through it from the microphone. Here it is the blackened *area* of the sound track (see opposite page) rather than its *density* which reproduces the wave form of the original speech. The photoelectric cell then functions in precisely the same way with the variable-width sound track as with the variable-density track. Both methods give amazingly accurate speech reproduction, as everyone who has listened to the presentation of a modern high-fidelity sound motion picture will agree.

Summary. **The fundamental of a closed pipe has a wave length four times as long as the pipe; that of an open pipe has a wave length twice as long as the pipe.**

An open pipe has both odd and even harmonics, whereas a closed pipe has odd harmonics only.

Four kinds of microphone have been widely used: (1) the carbon transmitter, (2) the iron-disk receiver, (3) the condenser microphone, (4) the moving-coil microphone. For accurate speech reproduction the last has largely replaced the other three.

All sound-reproducing instruments now transform sound-wave forms into varying electric currents of the same wave forms, then amplify these currents without distortion, and finally transform them back again into the mechanical wave forms.

There are two kinds of motion-picture films: those having variable-density sound tracks and those having variable-width sound tracks.

QUESTIONS AND PROBLEMS

A

1. The ceiling of a small chapel was found to be too low to permit installing the 16-foot open pipe of the organ. How could the pipe have been altered for installation without changing its pitch?

2. Why is the quality of an open organ pipe different from that of a closed organ pipe?

3. Explain how an instrument like the bugle, which has an air column of unchanging length, may be made to produce several notes of different pitch, as C, G, C′, E′, G′. (C is seldom used.)

4. Why is the pitch of a sound emitted by a phonograph raised by increasing the speed of rotation of the disk?

5. What evidence have you that sound waves are longitudinal vibrations?

B

1. In making a lateral-cut phonograph record, what visible effect will be produced on the disk (*a*) if the loudness of the note is increased? (*b*) if the pitch is lowered an octave?

2. Mention two musical instruments, the first of which depends upon resonance and the second upon forced vibrations for sound intensification.

3. What proves that a musical note is transmitted as a wave motion?

4. What will be the relative lengths of a series of organ pipes which produce the eight notes of a diatonic scale?

5. The velocity of sound in hydrogen is about four times as great as it is in air. If a C pipe is blown with hydrogen, what will be the pitch of the note emitted?

6. What must be the length of a closed organ pipe which produces the note E? (Take the speed of sound as 340 m/sec.)

7. What is the first overtone which can be produced in an open G organ pipe?

8. What is the first overtone which can be produced by a closed G organ pipe?

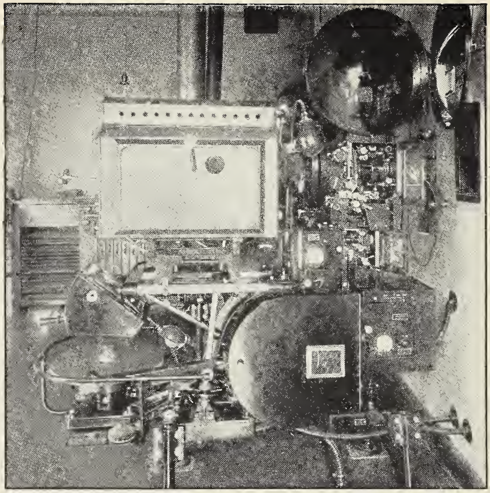
9. Explain the mechanism of production of musical sounds in each of the instruments shown on pages 473 and 475.

10. An open organ pipe is 3.5 ft long. What is the frequency of its fundamental tone if the speed of sound is 1120 ft/sec?

11. Explain how a moving-coil microphone works.

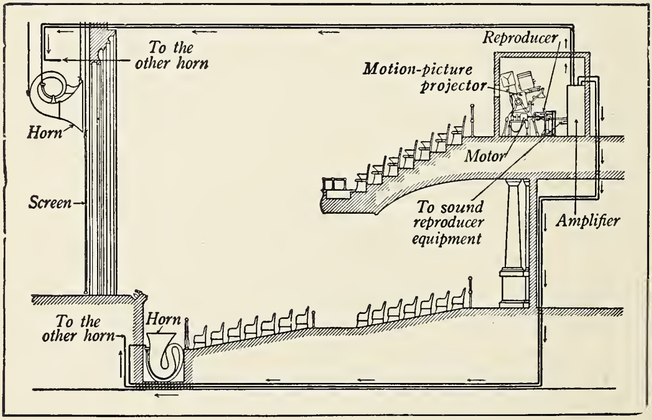
12. Discuss the differences between moving-coil microphones and moving-coil loud-speakers.

13. Trace the energy changes in the recording and reproduction of a phonograph record.



A Modern Motion-Picture Projector

Courtesy of the Electrical Research Products Company



A Cross Section of a Typical Motion-Picture Theatre

Courtesy of the Western Electric Company of New York

UNIT SIX

Light

Most of what we know of the world about us we learn through our eyes, that is, through the medium of light. Long before there was any science, men watched in wonder the movements of the sun and stars, trying to guess the mystery of the extraordinary display of the heavens. Their guesses were quite at random and of no value until, at the dawn of recorded history, six thousand years ago, the Egyptians began to look at the heavens more accurately. Perhaps the first step in science was taken when they noticed that the sun traveled a regular course through the fixed stars, returning to the same relative position every 365 days. The Great Pyramid, greatest of the tombs of the Pharaohs, was placed so as to serve as an astronomical instrument. It determined the time of the equinoxes, for on these days its east and west faces were just grazed by the rays of the rising and of the setting sun.

Again, several thousand years later, Copernicus (1473–1543), Galileo (1564–1642), and Newton (1642–1727), by observations of the light-emitting heavenly bodies, proved (1) that the earth, instead of being the center of all things, revolves around the sun, (2) that bodies are attracted to one another by a definite law, the law of gravitation, and (3) that they move in accordance with further definite laws, the laws of Newton and Galileo.

Later astronomers, such as Huygens and Römer, reflecting and experimenting to find out how light reaches us from the sun and the stars, how fast it travels, and

what happens when it passes from one substance into another, found the laws of refraction and reflection, and other laws, upon which practically all our modern optical instruments are based — telescopes, microscopes, and, most important of all, eyeglasses.

In modern times, by investigating light phenomena in great detail, scientists have pried into the interior of the atom in the quantum theory, and their newest discoveries have found practical application in sound motion pictures, in the almost instantaneous transmission of photographs by wire, in the first steps that have been taken in television, in color photography and printing, and in scores of other developments which are now part of our everyday lives.

The play of color which we see in the clouds, in the rainbow, in the iridescent hues of the hummingbird, in the great masterpieces of pictorial art, excites our admiration and wonder and is an intimate part of the living and enjoying of every man and woman on earth. What we shall study in the next few pages will open the door to the understanding of these things, which used to be thought of as mysteries, but of which the science of *light* has revealed the causes.

CHAPTER XVIII

Nature and Propagation of Light

Transmission of Light

Speed of light. Before the year 1675 it was thought that light required no time whatever to pass from the source to the observer. In that year, however, Olaus Römer, a young Danish astronomer, came to the following conclusion: He had observed accurately the instant at which one of Jupiter's moons, M (Fig. 432), passed into Jupiter's shadow when the earth was at E. He forecast, from the known time between such eclipses, the exact instant at which a given eclipse ought to occur six months later, when the earth should be at E'. It actually took place 16 minutes 36 seconds (or 996 seconds) later than he had predicted. Römer concluded that the 996 seconds' delay represented the time required for light to travel across the earth's orbit. This distance is now known to be about 186,000,000 miles. The speed of light is therefore 186,000,000 divided by 996, or about 186,000 miles per second. The most precise of modern measurements of the speed of light are made by laboratory methods. The generally accepted value, that of Michelson, formerly of The University of Chicago, is 299,774 kilometers per second. It is sufficiently correct

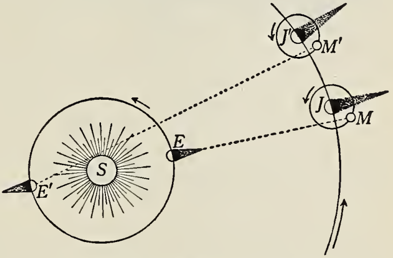


FIG. 432. Illustrating Römer's determination of the velocity of light

to remember it as 300,000 kilometers, or 186,000 miles. Though this speed would carry light around the earth $7\frac{1}{2}$ times in a second, yet this distance is so small in comparison with that of the stars that the light which is now reaching the earth from the nearest fixed star, Alpha Centauri, started 4.3 years ago. If an observer on the pole star had a telescope powerful enough to enable him to see events on the earth, he would not have seen the battle of Gettysburg (which occurred in July, 1863) until January, 1918. The distances of some of the spiral nebulae have been measured by E. P. Hubble of the Mt. Wilson Observatory, who finds them to be so astoundingly remote from us that the light by which we now see these nebulae started a hundred million years ago.

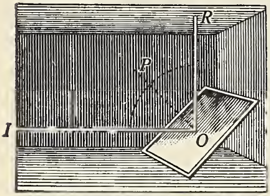


FIG. 433. Illustrating law of reflection of light

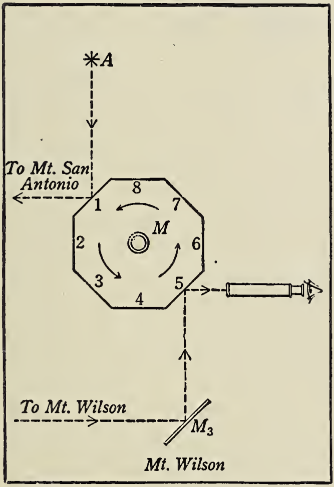
Both Foucault in France and Michelson in America measured directly the velocity of light in water and found it to be only three fourths as great as in air. It will be shown later that in all transparent liquids and solids it is less than it is in air.

Reflection of light. Admit a beam of sunlight to a darkened room through a narrow slit. The straight path of the beam will be made visible by the brightly illumined dust particles suspended in the air. Let the beam fall on the surface of a mirror. Its direction will be seen to be sharply changed, as shown in Fig. 433. Hold the mirror so that it is perpendicular to the beam. The beam will be seen to be reflected directly back on itself. Turn the mirror through an angle of 45°. The reflected beam will move through 90°.

The experiment shows roughly, therefore, that the angle *IOP*, between the ray approaching the mirror (called the *incident* beam) and the perpendicular to the mirror (called the *normal*), is equal to the angle *POR*, between the reflected beam and the normal to the mirror. The first angle, *IOP*, is

Albert A. Michelson
(1852–1931)

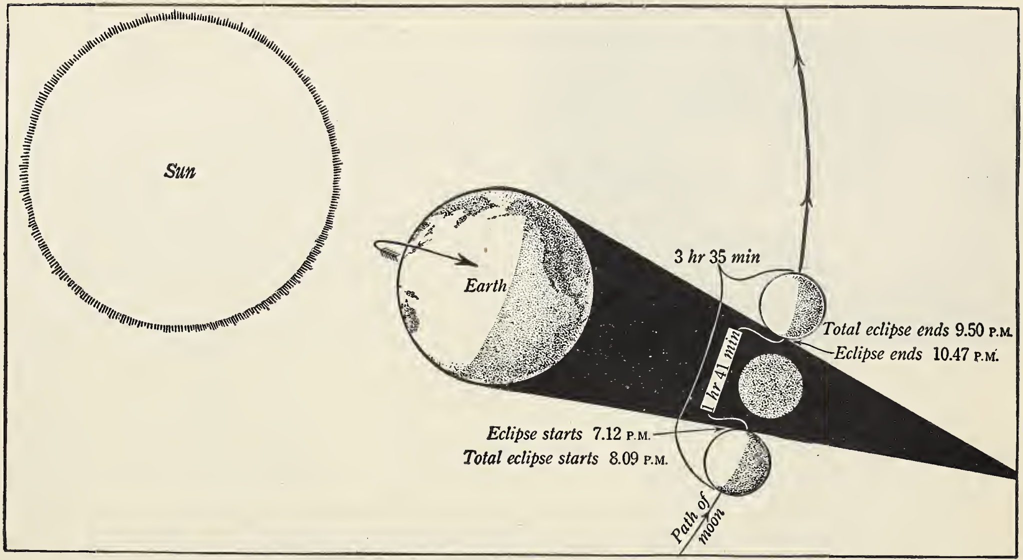
Professor of physics for forty years at The University of Chicago, foremost of modern contributors to the field of light. Famous for the extraordinary precision of his measurements. The Michelson-Morley experiment on the relative motion of earth and ether underlay and stimulated the development of the relativity theory



Michelson's Mean Measurement of the Speed of Light = 299,774 Kilometers per Second

The eight-faced mirror M can rotate very rapidly (up to 530 revolutions per second). Before it starts, a beam of light from A is reflected from face 1 to Mt. San Antonio, distant 22 miles (D), where a mirror returns it by way of M_3 to face 5. M is then started. When the speed is just such that the time required for light to go to Mt. San Antonio and back is the same as for face 4 to rotate into the exact position before occupied by face 5, A can again be seen precisely as at first. The known speed of the rotation gives this time (t). Then

$$V = \frac{2D}{t}$$



The Total Eclipse of the Moon, June 15, 1935

The moon is eclipsed by passing into the umbra of the earth. In this eclipse she was all the time visible because of scattered light and starlight but looked like a pale ghost of herself. The distance from the sun to the earth is so great that the penumbra was not here important. The times relate to Los Angeles, where this eclipse was notable

called the angle of incidence, and the second, *POR*, the angle of reflection. *The angle of reflection is equal to the angle of incidence.*

Diffusion of light. In the last experiment the light was reflected by a very smooth plane surface. Now allow the beam to fall upon a rough surface like that of a sheet of unglazed white paper. No reflected beam will be seen; but instead the whole room will be brightened appreciably, so that the outline of objects before invisible may be plainly seen.

The beam has evidently been scattered in all directions by the countless little reflecting surfaces which make up the surface of the paper. The effect will be much more noticeable

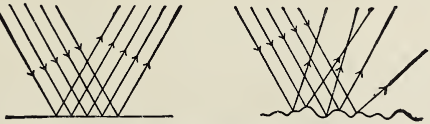


FIG. 434. Regular and irregular reflection

if the beam is allowed to fall first on a piece of dead-black cloth and then on the white paper. The light is largely absorbed by the cloth, whereas it is scattered, or *diffusely reflected*, by the paper. Illumination strong enough for sewing on white material may be altogether too weak for working on black goods. The difference between a smooth reflector and a rough one is illustrated in greatly magnified form in Fig. 434. The air shafts of apartment houses are made white to get the maximum diffusion of daylight into rooms that might otherwise be very dark.

Visibility of nonluminous bodies. Everyone is familiar with the fact that certain classes of bodies, such as the sun, a gas flame, etc., are self-luminous (visible on their own account), whereas other bodies, like books, chairs, tables, etc., can be seen only when they are in the presence of luminous bodies. The experiment above shows how such nonluminous, diffusing bodies become visible in the presence of luminous bodies.

For, since a diffusing surface scatters in all directions the light which falls upon it, each small element of such a surface is sending out light in a great many directions, in much the same way in which each point on a luminous surface is sending out light in all directions. Hence we always see the *outline* of a diffusing surface as we do that of an emitting surface, no matter from where we see it. On the other hand, when light comes to the eye from a polished reflecting surface, since the form of the beam is wholly undisturbed by the reflection, we see the outline not of the mirror but rather of the source from which the light came to the mirror. All bodies other than self-luminous ones are visible only by the light which they diffuse. Black bodies send no light to the eye, but their outlines can be distinguished by the light which comes from the background. Any object *which can be seen,* therefore, may be regarded as itself sending rays to the eye; that is, it may be treated as a luminous body.

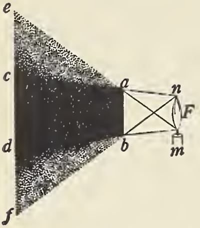


FIG. 435. Shadow from a broad source

Shadows. Hold any opaque object very close to a white screen placed opposite a window or a broad gas flame. So long as the object is very close to the screen the shadow is uniformly dark, but as it is moved toward the source of light (*F*, Fig. 435) two parts to the shadow will be observed: a very black part, *cd*, in the middle, from which all the light from the source is excluded; and a part, *ec* and *df*, which grows gradually lighter with distance from the dark center *cd*.

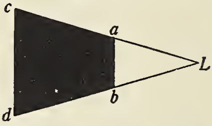


FIG. 436. Shadow from a small source

These effects show that light travels in straight lines. The region *abcd*, from which the light from all points of the source *mn* is excluded, is called the *umbra.* The region *ace* and *bdf*, which receives light from some portions of the source but not from all, is called the *penumbra.* It will be seen from the figure that the *penumbra* must decrease

as the object approaches the screen, and also as the size of the source diminishes. When the source becomes a mere point, there is no penumbra at all (Fig. 436). When the source is larger than the opaque object, as in the case of the sun and earth, the umbra is a cone, as shown opposite page 489.

Summary. **The velocity of light is 300,000 kilometers per second, or 186,000 miles per second.**

The angle of reflection equals the angle of incidence.

Diffusion of light is its irregular reflection.

Nonluminous bodies are seen by the light which they diffuse. A perfect reflector would be invisible.

Light travels in straight lines.

QUESTIONS AND PROBLEMS

A

1. Sirius, the brightest star, is about 52,000,000,000,000 mi away. If it were suddenly destroyed, how long would it shine on for us?

2. Devise an arrangement of mirrors by means of which you could see over and beyond a high stone wall or trench embankment. This is a very simple form of periscope.

3. Why is a room with white walls much lighter than a similar room with black walls?

4. (*a*) Compare the reflection of light from white blotting paper with that from a plane mirror. (*b*) Which of these objects is more easily detected from a distance? (*c*) Why?

5. If the word *white* be painted with white paint (or whiting moistened with alcohol) across the face of a mirror and held in the path of a beam of sunlight in a darkened room, in the middle of the spot on the wall which receives the reflected beam the word *white* will appear in black letters. Explain.

B

1. Show by a diagram the relative positions of the earth, the sun, and the moon during a total eclipse of the moon, indicating by lines the umbra of the earth and by a dot the position of the observer.

2. (*a*) Explain a total eclipse of the sun by the method used in Problem 1. (*b*) Explain similarly a partial eclipse of the sun.

3. Will it ever be possible for the moon totally to eclipse the sun from the whole of the earth's surface at once?

4. The diameter of the moon is 2000 mi and that of the sun 860,000 mi, and the sun is 93,000,000 mi away. What is the length of the moon's umbra?

5. If the distance from the center of the earth to the center of the moon were exactly equal to the length of the moon's umbra, over how wide a strip on the earth's surface would the sun be totally eclipsed at any one time?

6. Look at the reflected image of an electric-light filament in a piece of red glass. Why are there two images, one red and one white?

7. The earth reflects sixteen times as much light to the moon as the moon does to the earth. (*a*) Trace from the sun to the eye of the observer the light by which he is able to see the dark part of the new moon. (*b*) Why can we not see the dark part of a third-quarter moon?

Illumination and Photometry

Intensity of illumination. We notice that as we get farther away from a light, it becomes less and less bright. But in physics we are not satisfied with this rough description. We wish to determine exactly this relation between brightness, or intensity, and distance.

Set four candles as close together as possible in such a position *B* as to cast upon a white screen *C*, placed in a well-darkened room, a shadow of an opaque object *O* (Fig. 437). Place one candle in such a position *A* as to cast another shadow of *O* upon the screen. Since light from *A* falls on the shadow cast by *B*, and light from *B* falls on the shadow cast by *A*, it is clear that the two shadows will appear equally dark only when light of equal intensity falls on each; that is, when *A* and *B* produce equal illumination upon the screen. Shift the positions of *A* and *B* until this condition is fulfilled. Then measure the distances from *B* to *C* and from *A* to *C*. If all five candles are burning with flames of the same size, the first distance will be found to be just twice as great as the second. Hence the illumination produced upon the screen by each one of the candles at *B* is but one fourth as great as that produced on the screen by one candle at *A*, one half as far away.

This is the direct experimental proof that *the intensity of illumination varies inversely as the square of the distance from the source.*

This method of comparing experimentally the intensities of two lights was first used by Count Rumford. The arrangement is therefore called the *Rumford photometer* (light-measurer).

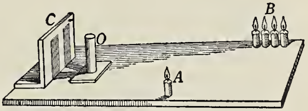


FIG. 437. Rumford's photometer

The theoretical proof of the law is furnished at once by Fig. 438, for since all the light which falls from the candle L on A is spread over four times as large an area when it reaches B, twice as far away, and over nine times as large an area when it reaches C, three times as far away, obviously the *intensities* at B and at C can be but one fourth and one ninth as great as at A.

Candle power and foot-candle. The last experiment furnishes a method of comparing the *light-emitting powers* of various sources of light. For example, suppose that the four candles at B are replaced by a flashlight bulb, and that for the condition of equal illumination upon the screen the two distances BC and AC are the same as those given above, namely, 2 to 1. We should then know that the bulb, which is

FIG. 438. Proof of law of inverse squares

able to produce the same illumination at a distance of 2 feet as a candle at a distance of 1 foot, has a light-emitting power equal to four candles. In general, then, *the candle powers of any two sources which produce equal illumination on a given screen are directly proportional to the square of the distances of the sources from the screen.*

It is customary to express the intensities of all sources of light in terms of candle power (cp), 1 candle power being

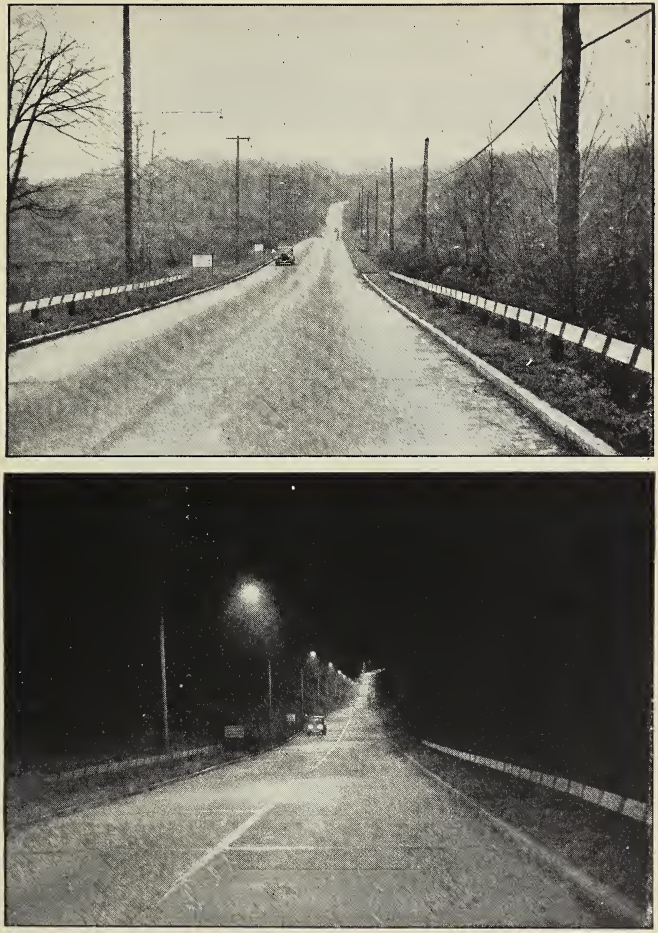
defined as the amount of light emitted by a sperm candle $\frac{7}{8}$ inch in diameter and burning 120 grains (7.776 grams) per hour. A 25-watt lamp will give about 20 candle power and a 50-watt lamp about 40 candle power. The intensity of such a lamp diminishes somewhat with age.

A standard candle at a distance of 1 foot gives an intensity of illumination called a *foot-candle* (*ft-c*). A 100-candle-power lamp, for example, at a distance of 1 foot gives an intensity of illumination of 100 foot-candles; at 2 feet, of 25 foot-candles; at 5 feet, of 4 foot-candles; and at 10 feet, of 1 foot-candle. In general, foot-candles = candle power/feet^2. In ordinary rooms the intensity of illumination does not fall off so fast because of diffusion of light by the walls. (The foot-candle meter is described opposite page 495.)

Instead of measuring the candle power of a lamp, illuminating engineers often measure the total light emitted in *lumens* (see page 385).

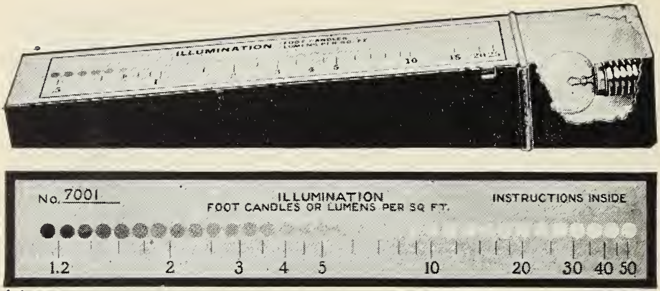
[Bunsen's photometer. Robert Bunsen, a German chemist and inventor responsible for the Bunsen burner, wanted to find some more accurate method of measuring intensities than the one described above. Let us see how he went about it.

[Place a drop of oil or melted paraffin in the middle of a sheet of unglazed white paper so that light will show through it. Hold the paper near a window and observe the side *away from* the window. The oiled spot will appear *lighter* than the remainder of the paper. Then hold the paper so that the side nearest the window may be seen. The oiled spot will appear *darker* than the rest of the paper. We learn, therefore, that *when the paper is viewed from the side of greater illumination, the oiled spot appears dark*; but *when it is viewed from the side of lesser illumination, the spot appears light.* If, then, the two sides of the paper are equally illuminated, the spot ought to be of the same brightness when viewed from either side. Darken the room and place the oiled paper between two gas flames, two electric lights, or any two equal sources of light. You will notice that when the paper is held closer to one than the other, the spot will appear dark when viewed from the side next the closer light; but if it is then moved until it is nearer the other source, the spot will change from dark to light when viewed always from the same

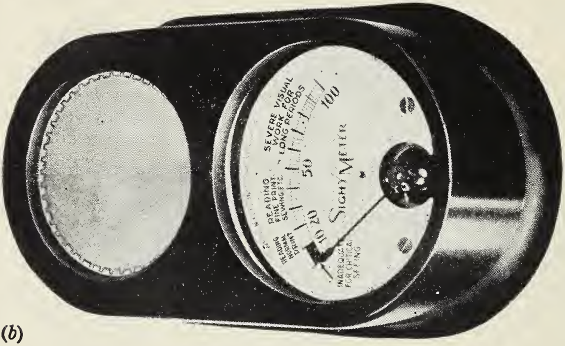


Day and Night Views of an Ohio Highway (Modern Lighting System)

On unlighted highways motoring fatalities are 64 per cent higher at night than in the daytime. (Courtesy of the General Electric Company)



(*a*)



(*b*)

Foot-candle Meters

(*a*) This foot-candle meter makes use of a series of highly translucent spots located at increasing distances from a small incandescent lamp placed inside a dark box near one end of the series of spots. The spots are therefore illuminated by the small working standard with intensities calibrated empirically in foot-candles that diminish with distance from the lamp. When the meter is placed to receive light from an external source, all the spots receive the same intensity of illumination from without. That particular spot which is equally illuminated on both sides becomes invisible, thus indicating the intensity of illumination of the outside source in foot-candles.

(*b*) The Weston photoelectric foot-candle meter is merely a photoelectric cell (see Chapter XXIII) the currents from which go through a Weston milliammeter. The scale is calibrated by comparison with a standard foot-candle meter, so that the illumination is read off directly. (Courtesy of the Weston Electrical Instrument Corporation)

side. It is always possible to find some position for the oiled paper at which the spot either disappears altogether or at least appears the same when viewed from either side. This is the position at which the illuminations from the two sources are equal. Hence, to find the candle power of any unknown source it is only necessary to set up a candle on one side and the unknown source on the other, as in Fig. 439, and to move the spot *A* to the position of equal illumination. The candle power of the unknown source at *C* will then be the square of the distance from *C* to *A*, divided by the square of the distance from *B* to *A*.

This arrangement is known as the *Bunsen photometer.*

Proper lighting. Statistics show that out of every 100 persons under twenty years of age about 20 have defects in vision. These defects increase rapidly with age, until at the age of sixty 82 out of every 100 have defective vision. The oculist has helped nature by providing corrective lenses. Lighting experts are beginning to show us how to select and place our light fixtures so that we may use our eyes with the minimum of eyestrain.

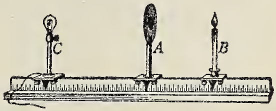


FIG. 439. Bunsen's photometer

The extent to which we see things well depends on their size, their contrast with the background, their brightness, and the time of exposure. After much experimentation a large newspaper has recently changed its style and size of type to produce greater legibility and reduce eyestrain. Objects to be seen well must be well illuminated but without glare. Glare is produced when the brightness, the volume of light, and the contrast with the background become too great. Indirect lighting, in which no direct rays fall on the place where the light is used, approaches more nearly that of natural daylight and, though more expensive, is to be preferred.

The amount of illumination required in the home or elsewhere depends upon the use to which it is put. The table on the following page gives some approximate values for the home.

Average Requirements in Foot-candles

	Foot-candles		Foot-candles
Porch	0.5	Library, general	3 to 4
Hall	2	Kitchen	6 to 10
Drawing-room	4	Bedroom	
Sitting-room	2 to 5	General	2
Dining-room		Dressing-table	6 to 10
General	2	Sewing-room, local	10 to 30
Over table	6 to 10	Reading	10 to 3C

Summary. **The intensity of light varies inversely with the square of the distance from its source.**

The candle powers of any two sources which produce equal illumination on a given screen are directly proportional to the squares of the distances of the sources from the screen; that is,

$$\frac{cp_1}{cp_2} = \frac{d_1^2}{d_2^2}.$$

A foot-candle is the intensity of illumination of a 1-candle-power light at a distance of 1 foot.

QUESTIONS AND PROBLEMS

A

1. (*a*) Distinguish between intensity of a source of light and intensity of illumination. (*b*) In what unit is each measured?

2. State in terms of a literal proportion the relationship between light intensity and distance from source.

3. In what two ways could the foot-candles of illumination falling on your work be increased?

4. What is the intensity of illumination on your desk if it is 4 ft away from an electric lamp giving 64 candle power?

5. If the sun were at the distance of the moon from the earth, instead of at its present distance, how much stronger would sunlight be than at present? (The moon is 240,000 mi and the sun 93,000,000 mi from the earth.)

6. If 5 sec is the proper length of exposure when you are printing photographs by an electric light 2 ft from the printing frame, wha'

length of exposure would be required in printing from the same negative at a distance of 4 ft from the same light?

7. If 10 ft-c is the proper illumination for reading, how far from the page of a book should a 90-candle-power light be placed in order to give this illumination?

B

1. If a 20-second photographic exposure is correct at a distance of 6 in. from an 8-candle-power electric light, what is the required time of exposure at a distance of 12 in. from a 32-candle-power electric light?

2. A standard candle furnishes the same intensity of light upon a screen 2 ft distant as another source of light furnishes when at a distance of 8 ft. (*a*) What is the candle power of the second light? (*b*) How great is the intensity of illumination of the screen in foot-candles when one of these lights shines upon it?

3. If a gas flame is 300 cm from the screen of a Rumford photometer, and a standard candle 50 cm away gives a shadow of equal intensity, what is the candle power of the gas flame?

4. Which has the greater luminous efficiency, a lamp rated at 1.3 watts per candle power or one rated at 1.5 watts per candle power? Why?

5. If a 4-candle-power light at a distance of $\frac{1}{2}$ ft gives enough illumination for reading, how far away must a 64-candle-power lamp be placed to give the same illumination? How strong a lamp should be used at a distance of 8 ft from the book?

6. If the page of your book is sufficiently illuminated at a distance of 3 ft from a 100-candle-power lamp, how many candle power will be needed when you move 2 ft farther away?

The Wave Theory of Light

The corpuscular theory of light. All the properties of light which have so far been discussed are perhaps most easily accounted for on the hypothesis that light consists of streams of very minute particles, or *corpuscles*, projected with the enormous velocity of 300,000 kilometers per second from all luminous bodies. The fact that light is both emitted and reflected in straight lines is exactly what we should expect

if this were the nature of light. The facts of refraction (p. 504) can also be accounted for, although somewhat less simply, on this hypothesis. As a matter of fact, this theory of the nature of light, known as the *corpuscular theory*, was the one most generally accepted up to about 1800.

The wave theory of light. A rival hypothesis, which was first completely stated by the great Dutch physicist Huygens (1629–1695), regarded light, like sound, as a *form of wave motion*. This hypothesis met at the start with two very serious difficulties. In the first place, light, unlike sound, not only travels with perfect readiness through the best vacuum which can be obtained with an air pump, but it travels without any apparent difficulty through the great spaces between stars, which are probably infinitely better vacua than can be obtained by artificial means. If, therefore, light is a wave motion, it must be a wave motion of some medium which fills all space and yet does not hinder the motion of the stars and planets. Huygens assumed such a medium to exist, and called it the *ether*. In some quarters today the word *ether* is not in favor; instead the property of transmitting waves is assigned to space itself. This amounts essentially to adopting Huygens's point of view but using the word *space* in place of the word *ether*.

The second difficulty in the way of the wave theory of light was that it apparently failed to account for the fact that light travels in straight lines. Sound waves, water waves, and all other forms of waves with which we are most familiar bend readily around corners, whereas light apparently does not. It was this difficulty chiefly which led many of the most famous of the early philosophers, including the great Sir Isaac Newton, to reject the wave theory and to support the projected-particle theory. Within the last hundred years, however, this difficulty has been completely removed, and in addition other properties of light have been discovered for which the wave theory offers the most satisfactory explanation. The most important of these properties will be treated in the next paragraph.

Interference of light. Let two pieces of plate glass about $\frac{1}{2}$ in. wide and 4 or 5 in. long be separated at one end by a thin sheet of paper in the manner shown in Fig. 440. At the other end clamp them or hold them firmly together, so that a very thin wedge of air exists between them. Soak a piece of asbestos or blotting paper in a solution of common salt (sodium chloride) and place it over the tube of a Bunsen burner so as to touch the flame in the manner shown. The flame will be colored a bright yellow by the sodium in the salt. When the eye looks at the reflection of the flame from the glass surfaces, a series of fine black and yellow lines will be seen to cross the plate.

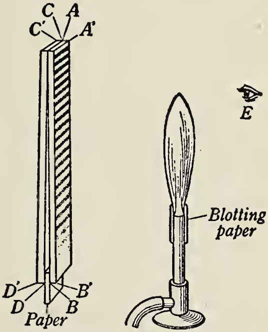


Fig. 440. Interference of light waves

The wave theory offers the following explanation of these effects. Each point of the flame sends out light waves which travel to the glass plate and are in part reflected and in part transmitted at all the surfaces of the glass, that is, at $A'B'$, at AB, at CD, and at $C'D'$ (Fig. 440). We will consider, however, only those reflections which take place at the two faces of the air wedge, namely, at AB and CD. Let Fig. 441 represent a greatly magnified section of these two surfaces. Let the wavy line *as* represent a light wave reflected from the surface AB at the point a, and returning thence to the eye. Let the dotted wavy line *ir* represent a light wave reflected from the surface CD at the point i, and returning thence to the eye. Similarly let all the continuous wavy lines of the figure represent light waves reflected from different points on AB to the eye, and let all the dotted wavy lines represent waves reflected from corresponding points on CD to the eye. Now, in precisely the same way in which two trains of sound waves from two tuning forks were found, in the experiment illustrating beats (p. 468), to interfere with each other so as to produce silence whenever the two waves corresponded

to motions of the air particles in opposite directions, so in this experiment the two sets of light waves from *AB* and *CD* interfere with each other so as to produce darkness wherever these two waves correspond to motions of the light-transmitting medium in opposite directions. The dark bands, then, of our experiment are simply the places at which the two beams reflected from the two surfaces of the air film neutralize, or destroy, each other, whereas the light bands correspond to the places at which the two beams reinforce each other and thus produce illumination of double intensity. The position of the second dark band *c* must of course be determined by the fact that the distance from *c* to *k* and back (Fig. 441) is a wave length more than from *a* to *i* and back, and so on down the wedge. This phenomenon of the interference of light is met with in many different forms, and in every case the wave theory furnishes at once a wholly satisfactory explanation of the observed effects. The corpuscular theory in its original form, on the other hand, is unable to account for any of these interference effects. However, some new phenomena, called *photoelectric effects* (pp. 603–606), have recently been discovered which can be more easily interpreted by some modified form of the corpuscular theory than by the wave theory. But, for the understanding and remembering of the most familiar properties of light, it is still necessary, and probably will always continue to be necessary, to think in terms of waves. Indeed, we know definitely that light waves are just

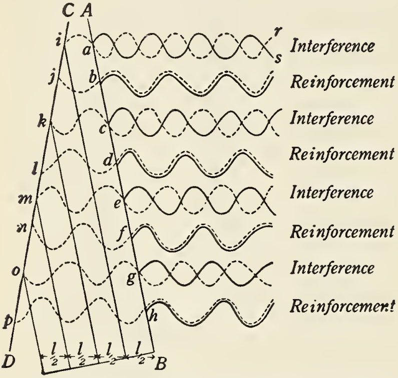


FIG. 441. Explanation of formation of dark and light bands by interference of light waves

like wireless waves except that they are of very much shorter wave length. So that both phenomena must be interpreted by the same sort of modification of the wave theory, if that theory is to be modified at all, as now seems pretty certain.

The ether. We have already indicated that if the wave theory is to be used, we must conceive, with Huygens, that all space is filled with a wave-transmitting medium, which may be space itself, if we see fit to give it such a property. This medium certainly cannot be like any of the ordinary forms of matter; for, if any of these forms existed in interplanetary space, the planets and the other heavenly bodies would certainly be retarded in their motions. As a matter of fact, in all the hundreds of years during which astronomers have been making accurate observations of the motions of heavenly bodies, no such retardation has ever been observed. The medium which transmits light waves must therefore have a density which is infinitely small even in comparison with that of our lightest gases.

Further, in order to account for the transmission of light through transparent bodies, it is necessary to assume that "ether" is like space itself in that it is present not only in all interstellar spaces (between stars) but in all intermolecular spaces as well.

Wave length of yellow light. Although light, like sound, acts as if it were a form of wave motion, light waves differ from sound waves in several important respects. In the first place, an analysis of the preceding experiment shows that the wave length of light is extremely minute in comparison with that of ordinary sound waves. The wave length of the yellow light used in that experiment is .00006 centimeter (about $\frac{1}{40,000}$ inch).

The *number of vibrations per second* of light waves may be found, as in the case of sound, by dividing the velocity by the wave length. Since the velocity of light is 30,000,000,000 centimeters per second and the wave length is .00006 centimeter, the number of vibrations per second of yellow light has the enormous value 500,000,000,000,000.

Light waves transverse. Thus far we have discovered but two differences between light waves and sound waves; namely, the former are disturbances in some medium other than matter and always travel with the enormous speed of 186,000 miles per second in a vacuum, whereas the latter are certainly disturbances in ordinary matter and travel 1100 feet per second in air and a few times faster in liquids and solids. There exists, however, a further radical difference, which follows from a capital discovery made by Huygens in the year 1690. It is this: While sound waves consist, as we have already seen, of *longitudinal* vibrations of the transmitting medium, that is, vibrations back and forth in the line of propagation of the wave, light waves are like the water waves of Fig. 393 (p. 439) in that they consist of *transverse* vibrations, that is, vibrations at right angles to the direction of the line of propagation.

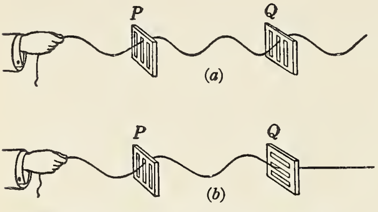


FIG. 442. Transverse waves passing through slits

In order to appreciate the difference between the behavior of waves of these two types under certain conditions, conceive of transverse waves in a rope being made to pass through two gratings in succession, as in Fig. 442. So long as the slits in both gratings are parallel to the plane of vibration of the hand, as in Fig. 442 (*a*), the waves can pass through them with perfect ease; but if the slits in the first grating *P* are parallel to the direction of vibration, and those of the second grating *Q* are turned at right angles to this direction, as in Fig. 442 (*b*), it is evident that the waves will pass readily through *P*, but will be stopped completely by *Q*, as shown in the figure. In other words, these gratings *P* and *Q* will let

FIG. 443. Tourmaline tongs

through such and only such transverse vibrations as are parallel to the direction of their slits.

If, on the other hand, a longitudinal instead of a transverse wave — for example, a sound wave — had approached such a grating, it would have been as readily transmitted in one position of the grating as in another, since a *to-and-fro* motion can evidently pass through the slits with exactly the same ease, no matter how they are turned.

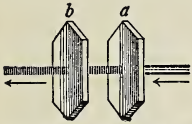


FIG. 444. Light passing through tourmaline crystals

Now two crystals of tourmaline are found to behave with respect to light waves just as the two gratings behave with respect to the waves on the rope.

Hold one such crystal, *a* (Fig. 443), in front of a small hole in a screen through which a beam of sunlight is passing to a neighboring wall; or, if the sun is not shining, simply hold the crystal between the eye and a source of light. The light will be readily transmitted, although somewhat diminished in intensity. Then hold a second crystal, *b*, in line with the first. The light will still be transmitted, *provided the axes of the crystals are parallel*, as is shown in Fig. 444. When, however, one of the crystals is rotated in its ring through 90° (Fig. 445), the light is *cut off*. This shows that a crystal of tourmaline can transmit only light which is vibrating in one particular plane.

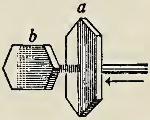


FIG. 445. Light cut off by crossed tourmaline crystals

From this experiment, therefore, we are forced to conclude that *light waves are transverse rather than longitudinal vibrations*. The beam of light as it approached the first crystal may be thought of as composed of transverse vibrations in all possible planes across the line of propagation, as illustrated in Fig. 446. Only the vibrations in say the vertical plane could pass through the first crystal. This is why the intensity of the light was so reduced by that crystal. All the vertical vibrations that pass through the first crystal are cut off by the second when its axis is turned at right angles to

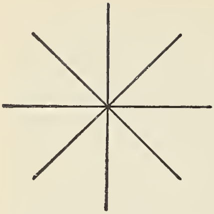


FIG. 446. Cross section of approaching light wave

that of the first. The experiment illustrates what is technically known as the *polarization of light*. The beam which, after passage through *a*, is unable to pass through *b* if the axes of *a* and *b* are crossed, is known as a *polarized beam*. It is, then, the phenomenon of the *polarization of light* upon which we base the conclusion that light waves are transverse.

Summary. **Interference phenomena indicate that light is a wave motion.**

Polarization phenomena indicate that light waves are transverse.

QUESTIONS AND PROBLEMS

1. Describe the strongest experimental evidence you know for the wave theory of light.

2. List five ways in which light waves differ from sound waves.

3. Describe the experimental evidence for the theory of the transverse character of light waves.

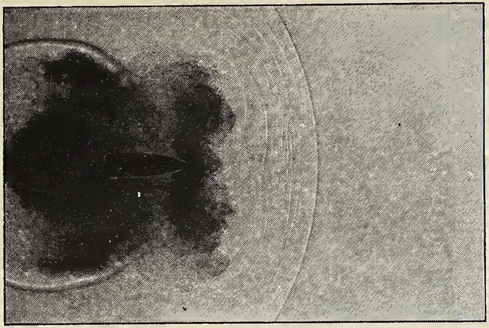
4. What is meant by saying that a beam of light is polarized?

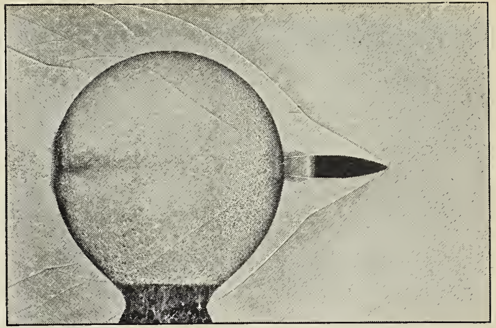
Refraction of Light

Refraction. The water in a tank never looks as deep as it is. Similarly objects under water always look nearer to the surface than they actually are. This suggests that possibly the light is bent in some way. Let us investigate this phenomenon more closely.

Allow a narrow beam of sunlight to fall on a thick rectangular glass plate with a polished front and whitened back* (Fig. 447). It will be seen to split into a reflected and a transmitted portion. The transmitted portion will be seen to be bent toward the perpendicular *OP* drawn into the glass. Upon reaching the air it will again be seen

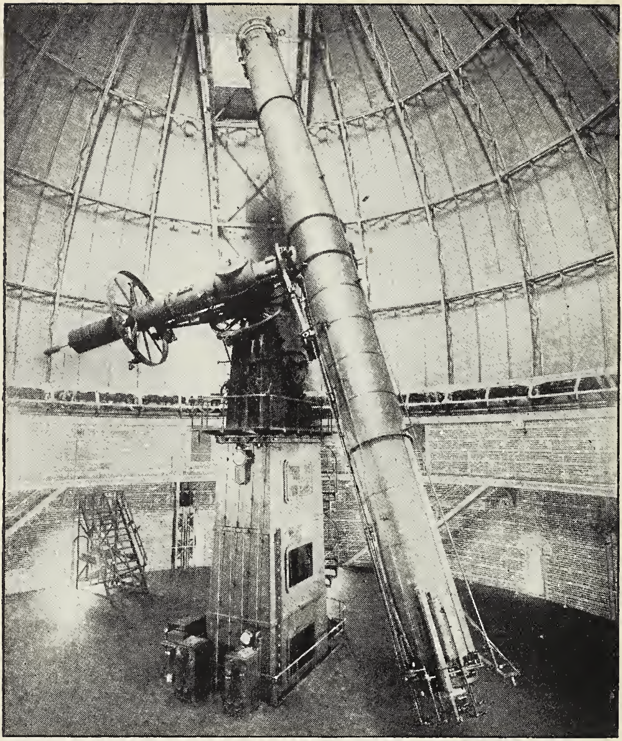
* All these experiments on reflection and refraction may be done effectively and conveniently by using disks of glass, like those used with the Hartl optical disk (Fig. 460), through which the beam can be traced.





Shadow Photograph of a Bullet in Full Flight

These are shadows cast upon the photographic plate by (1) the passing bullet, (2) the sound waves, (3) irregular turbulences in the air, (4) grains of powder, etc. At the instant the bullet was passing before the photographic plate in a perfectly dark room a brilliant electric spark was produced, thus causing an instantaneous shadow. The bullets shown are .30-caliber service projectiles fired from a Springfield rifle, the duration of the electric spark being 1/500,000 of a second. In the midst of the black cloud of powder particles is faintly seen the bullet, actually $1\frac{1}{2}$ inches in front of the muzzle and traveling with a speed of 2700 feet per second. The faint spherical sound wave seen ahead of the mushroom-shaped body of gas is a compressional wave started in the barrel by the movement of the bullet in leaving its cartridge case. The black area in front of the bullet represents gases that leaked past the bullet and got out ahead of it, and that behind it consists of propelling gases. The smaller but more intense sound wave is the chief cause of the report of the rifle. The picture to the right is a rifle bullet after passing through a soap bubble filled with a mixture of air and hydrogen, through which sound travels with a speed of 3200 feet per second, or 500 feet per second faster than the bullet. From an inspection of this picture it will be seen how both the head and base waves of the bullet have been modified by the high velocity of sound in the air-hydrogen mixture. (See page 586)



The Great Telescope of the Yerkes Observatory (The University of Chicago)

This is the largest *refracting* telescope in the world. The objective is an achromatic lens (see page 548) 40 inches in diameter, which is mounted in a tube 63 feet long. In order to follow the apparent motions of the heavenly bodies due to the rotation of the earth, the entire tube and counterpoises, weighing 21 tons, are driven by a giant clock. The speed of the clock is controlled by a governor, similar in principle to that of Fig. 205. By means of electric motors the telescope may be pointed in any direction. It is then clamped to the clock, which keeps it pointed toward the same region of the sky as long as may be desired. The entire floor may be raised or lowered to accommodate the observer

to split into a reflected and a transmitted portion, but the part passing into the air will this time be bent away from the perpendicular $O'P'$ drawn into the air. Let the incident beam strike the surface at different angles. It will be seen that *the greater the angle of incidence, the greater the bending.* When the beam of light is perpendicular to the glass, there will be no bending at all. If the upper and lower faces of the glass are parallel, the bending at the two faces will always be the same; consequently the emergent beam is parallel to the incident beam.

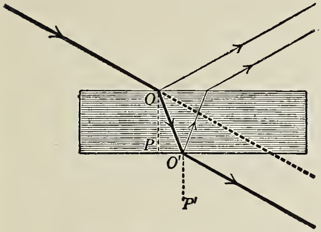


FIG. 447. Path of a ray through a medium bounded by parallel faces

As before, let a narrow beam of sunlight fall upon a glass prism cut out of a thick plate of glass. The greater portion of the light will pass through as shown in Fig. 448. The bendings, as already seen, are first toward and then away from the perpendiculars OP and $O'P'$ respectively. Since the sides of the prism are *not* parallel, the emergent beam is not parallel to the incident beam. If a prism of the same material having a larger angle A is used, it will be seen that there is a larger deviation of the light from its original direction. As in the case of the plate, the beam will be split into reflected and transmitted portions on entering and on leaving the prism.

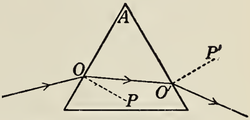


FIG. 448. Path of a ray through a prism

Similar experiments made with other substances have brought out the general law that *whenever light travels obliquely* (at an angle) *from one medium into another in which the speed is less, it is bent toward the perpendicular, and when it passes from one medium to another in which the speed is greater, it is bent away from the perpendicular drawn into the second medium.*

Total reflection; critical angle. Since rays emerging from a medium like water into one of less density, like air, are always bent *from* the perpendicular (IlA, ImB, etc., Fig. 449),

it is clear that if the angle of incidence on the undersurface of the water is made larger and larger, a point must be reached at which the refracted ray *InC* (Fig. 449) is *parallel to the surface.* It is interesting to inquire what will happen to a ray *Io* which strikes the surface at a still greater angle of incidence *IoP′*. It will not be unnatural to suppose that since the ray *nC* just grazed the surface, the ray *Io* will not be able to emerge at all. The following experiment will show that this is indeed the case:

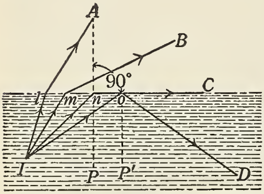


FIG. 449. Rays coming from a source *I* under water to the boundary between air and water at different angles of incidence

Hold a prism with three polished edges, a polished front, and a whitened back in the path of a narrow beam of sunlight, as shown in Fig. 450. If the angle of incidence *IOP* is small, the beam will divide at *O* into a reflected and a transmitted portion, the former going to *S′*, the latter to *S*. (Neglect the color for the present.) Rotate the prism slowly in the direction of the arrow. A point will be reached at which the transmitted beam disappears completely, while at the same time the spot at *S′* shows an appreciable increase in brightness. Since the transmitted ray *OS* has totally disappeared, the whole of the light falling on *O* must be in the reflected beam. The angle of incidence *IOP* at which this occurs is called the *critical angle.* This angle for crown glass is 42.5°; for water, 48.5°; for diamond, 23.7°. The critical angle for any substance may be defined as the angle of incidence in that substance for which the angle of refraction into air is 90°.

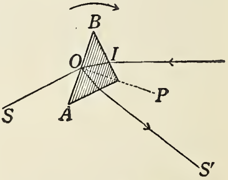


FIG. 450. Transmission and reflection of light at surface *AB* of a right-angled prism

We learn, then, that *when a ray of light traveling in any medium meets another medium in which the speed is greater, it is totally reflected if the angle of incidence is greater than a certain angle called the critical angle.*

A right-angled prism used as in Fig. 450 is a very efficient reflector, and is used practically in a number of devices, such as the periscope, the reflecting telescope, and high-grade binoculars (p. 537).

Wave-theory explanation of refraction. According to the wave theory a ray of light is in general merely *the direction of the perpendicular to the front of the advancing wave.* Thus in Fig. 451 the lines drawn at right angles to the line AB represent sections of the wave front taken at successive instants. When a portion of this wave front begins to enter the glass, the part that enters first begins to move forward more slowly, whereas the part that is still in the air continues to move forward at the old rate. The result, of course, is that the ray, that is, the perpendicular to the wave front, bends downward, as shown in the figure. This direction continues unchanged until the lower portion of the wave front emerges into the air again, when it speeds up and thus causes the ray to bend upward. That is, the ray bends toward the perpendicular drawn into the second medium when the speed decreases, and bends away when it increases.

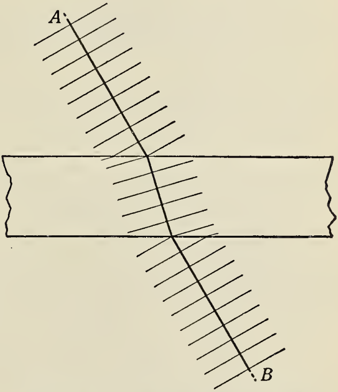


FIG. 451. Change in wave front due to refraction

Index of refraction. *The ratio of the speed of light in air to its speed in any other medium is called the index of refraction of that medium.* Fig. 452 shows how this ratio can be accurately determined simply from measuring the *angle of incidence, i,* of a ray as it passes from air into the second medium and also the *angle of refraction, r.* Thus the angle of incidence is by definition the angle i between an incident ray bb' and the

perpendicular $b'd$ to the surface, both drawn into the first medium. Similarly the angle of refraction is the angle r between the refracted ray and the perpendicular drawn into the second medium. The angles i and i', shown in the figure, are equal, since their sides are perpendicular each to each. Likewise the two angles r and r' are equal. But ab represents a section of the advancing wave just as its lower edge begins to touch the refracting surface, and $a'b'$ represents the same wave front at the instant at which its upper edge has just reached that surface. It is, then, at once obvious from the figure that

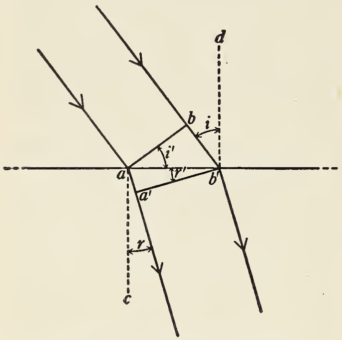


FIG. 452. Index of refraction

$$\frac{\text{Velocity in air}}{\text{Velocity in 2d medium}} = \frac{bb'}{aa'}.$$

But in the right-angled triangle abb' the ratio of the perpendicular bb' to the hypotenuse ab' is named sin i, and similarly by definition $aa'/ab' = \sin r$. Hence

$$\text{Index of refraction} = \frac{\text{velocity in air}}{\text{velocity in 2d medium}} = \frac{bb'}{aa'} = \frac{\sin i}{\sin r}.$$

So that it is necessary only to measure i and r or bb' and aa' to determine the velocity of light in the medium in question. The fact that this index is 1.33 for water means simply that the speed of light in air is 1.33 times its value in water.

The refractive indices of some of the commoner substances are as shown in the following table:

Water	1.33	Crown glass	1.53
Alcohol	1.36	Flint glass	1.67
Turpentine	1.47	Diamond	2.47

Summary. In passing into an optically denser medium light is bent toward the perpendicular drawn to the new medium, and in passing into an optically rarer medium it is bent away from the perpendicular.

Total reflection occurs when light tends to pass from a denser to a rarer medium at an angle greater than the critical angle.

The index of refraction of a substance is the ratio of the velocity of light in the air to its velocity in that substance.

QUESTIONS AND PROBLEMS

A

1. Draw diagrams to show in what way a beam of light is bent (*a*) in passing through a prism; (*b*) in passing obliquely through a plate-glass window.

2. Explain how the prism glass of the automobile headlight (Fig. 453) deflects the beam of light upon the road.

FIG. 453. Cross section of a headlight lens

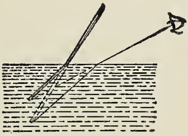


FIG. 454

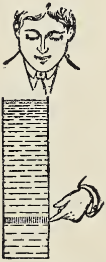


FIG. 455. Apparent depth of a body of water

3. A stick held in water appears bent, as shown in Fig. 454. Explain.

4. Show by a diagram and explanation what is meant by critical angle.

5. Look into a tall glass full of water, as in Fig. 455. Try to put your finger on the outside at the depth at which a penny on the bottom seems to be. Explain why you miss it by so much.

6. Explain why the sun is visible after it sinks below the horizon.

7. (*a*) What causes refraction? (*b*) When may light pass from one medium to another without bending?

8. How would light be refracted when going from alcohol into turpentine?

9. What practical use is made of the principle of total reflection?

B

1. Fig. 456 represents a section of a plate of prism glass. Explain why glass of this sort is so much more efficient than ordinary window glass in illuminating the rears of dark stores on the ground floor in narrow streets.

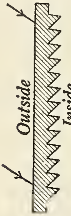


FIG. 456. A Luxfer prism glass

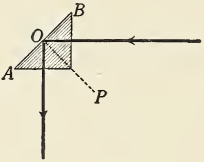


FIG. 457

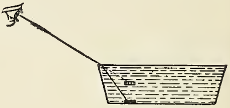


FIG. 458

2. A glass prism placed in the position shown in Fig. 457 is the most perfect reflector known. Why is it better than an ordinary mirror?

3. If a penny is placed in the bottom of a vessel in such a position that the edge just hides it from view (Fig. 458), it will become visible as soon as water is poured into the vessel. Explain.

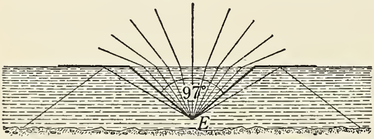


FIG. 459. To an eye under water all external objects appear to lie within a cone whose angle is 97°

4. Will a beam of light going from water into flint glass be bent toward or away from the perpendicular drawn into the glass?

5. (*a*) At what angle with the horizontal must a fish beneath the surface of water look in order to see the setting sun? (See Fig. 459.) (*b*) Can a fish see the fisherman in a boat on the surface of the water?

6. The moon has practically no atmosphere. We know this because when a star appears to pass behind the moon, there is no decrease or increase in its apparent velocity while disappearing or coming into view again. If the moon had an atmosphere like that of the earth, explain how this would affect the apparent velocity of the star at both these times.

7. Does a man above the surface of water appear to a fish to be farther from the surface than he actually is or nearer to it? Make an explanatory wave diagram.

8. When light passes obliquely from air into carbon disulfide, it is bent more than when it passes from air into water at the same angle. Is the speed of light in carbon disulfide greater or less than in water?

9. (*a*) What kind of glass should be used for making cut glass? (*b*) Why?

10. If light travels with a velocity of 186,000 mi/sec in air, what is its velocity (*a*) in water? (*b*) in crown glass? (*c*) in diamond? (See table of indices of refraction, p. 508.)

CHAPTER XIX

Image Formation

Images Formed by Lenses

Importance of refraction. It may seem strange that the education of millions of people depends on the simple principle of refraction outlined in the last chapter; yet such is the case. For education is obtained largely through reading, which in turn is possible only if we can see clearly. A large portion of the population can see clearly only with the aid of glasses, which are a direct practical application of the principle of refraction. In the following paragraphs we shall see just how the principle is applied:

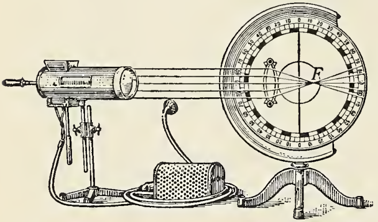


FIG. 460. Hartl optical disk

Focal length of a convex lens. Let a beam of light fall upon the convex glass of a Hartl optical disk (Fig. 460), or, in case this is not available, hold a convex lens in the path of a beam of sunlight which enters a darkened room, where it is made visible by means of chalk dust or smoke. The beam will be found to converge to a focus *F*, as shown in Fig. 461. Place a screen at *F*. The spot of intense brightness represents a very small image of the sun. Measure the distance from the lens to the "burning spot."

The explanation is as follows: The rays of light are parallel until they strike the lens. They are then bent in accordance with the laws given on page 505. The rays near the center of the lens are bent very little, those near the edge a great deal. The lens is so shaped that all the rays cross at *F*.

The wave explanation of the phenomenon is as follows: The waves from the sun or any distant object are without any appreciable curvature when they strike the lens; that is, they are so-called *plane waves* (Fig. 461). Since the speed of light is less in glass than in air, the central portions of these waves are retarded more than the outer portions in passing through the lens. Hence, on emerging from the lens these waves are concave instead of plane, and close in to a center, or *focus*, at F.

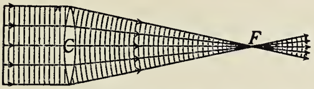


Fig. 461. Principal focus F and focal length CF of a convex lens

The line through the point C (the *optical center*) of the lens, perpendicular to its faces, is called the *principal axis*.

The point F at which rays parallel to the principal axis (incident plane waves) are brought to a focus is called the *principal focus*.

The distance CF from the center of the lens to the principal focus is called the *focal length* (f) of the lens.

Turn the lens used in the previous experiment toward a distant house and place a card (or, better, a mounted tracing-cloth screen) at the principal focus F (Fig. 462) as found by the "burning spot." A sharp image of the distant house will be formed upon the screen. If the eye is placed at least a foot directly behind the screen and the latter removed, the image of the house will be seen at the exact place where the screen was located. This sort of image which can be caught on a screen is called a *real image*.

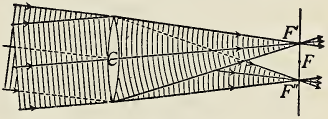


Fig. 462. Focal plane of a convex lens

The plane $F'FF''$ (Fig. 462) in which plane waves (parallel rays) coming to the lens from slightly different directions, as from the top and bottom of the distant house, all have their foci F', F'', etc. is called the *focal plane* of the lens. This is the position of a camera film with reference to its lens when a distant object is being photographed.

Since the rays converge at the point F, that point is the *center of curvature* of the waves coming from the lens. Now we define the *curvature* of any arc as 1 divided by the radius of the arc, or, in other words, as the reciprocal of the radius. In this case the radius of curvature of the wave emerging from the lens is the distance CF, or f. Hence the curvature of this wave is $1/f$. The curvature of the plane wave coming to the lens is obviously zero. Thus the lens has changed the curvature of the wave by the amount $1/f$. *No matter what the curvature of the wave striking the lens may be, the lens will always increase the curvature by this same amount,* $1/f$.

Conjugate foci. If a point source of light is placed at F (Fig. 461), it is obvious that the light which goes through

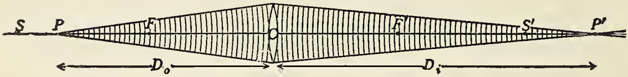


FIG. 463. Conjugate foci

the lens must exactly retrace its former path; that is, its waves will be rendered plane or its rays parallel by the lens. But if the point source P is at a distance D_o greater than f (Fig. 463), then the waves from P upon striking the lens have a curvature $1/D_o$ which is less than their former curvature, $1/f$. Since the lens was able to subtract all the curvature from waves coming from F (Fig. 461) and render them plane, it must render the flatter waves from P (Fig. 463) concave by subtracting the same curvature from them. That is, the rays after passing through the lens are converging and intersect at P'. If the source is placed at P', obviously the rays will meet at P. Points such as P and P', so related that one is the image of the other, are called *conjugate foci.*

Formula for conjugate foci; secondary foci. Since in Fig. 463 the curvature of the wave when it emerges from the lens is opposite in direction to its curvature when it reaches the lens, the *sum* of these curvatures, $1/D_o + 1/D_i$, represents the power of the lens to change the curvature of the incident

wave. But we have seen (p. 514) that this is always equal to $1/f$. Hence

$$\frac{1}{D_o}+\frac{1}{D_i}=\frac{1}{f}; \tag{1}$$

that is, *the sum of the reciprocals of the distances of the conjugate foci from the lens is equal to the reciprocal of the focal length.* If $D_o = D_i$, then the equation shows that both D_o and D_i are equal to $2f$. That is, if a point source of light is placed

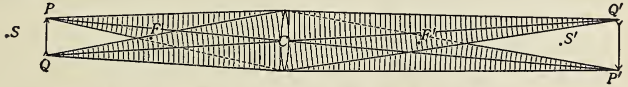


FIG. 464. Formation of a real image by a lens

at S two focal lengths from the lens (Fig. 463), the light passing from S through the lens will be brought to a focus at S', also two focal lengths from the lens.

The two conjugate foci S and S' which are at equal distances from the lens are called the *secondary foci.*

Images of objects. Place a candle or electric-light bulb between the principal focus F and the secondary focus S at PQ (Fig. 464), and place a screen of draftsman's tracing cloth at $P'Q'$. An enlarged inverted image will be seen upon the screen when viewed from either side.

This image is formed as follows: All the light which strikes the lens from the point P is brought together at a point P'. *The location of this image P' must be on a straight line drawn*

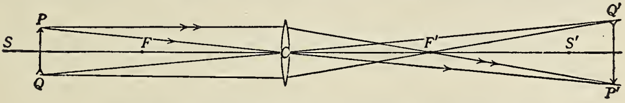


FIG. 465. Ray method of constructing an image

from P through C; for any ray passing through C will remain parallel to its original direction, since the portions of the lens through which it enters and leaves may be regarded as small parallel planes. (See page 505.) *The image $P'Q'$ is therefore*

always formed between the lines drawn from P and Q through C. If the focal length f and the distance of the object D_o are known, the distance of the image D_i may be obtained easily from equation (1).

The position of the image may also be found graphically as follows: Of the cone of rays passing from P to the lens, that ray which is parallel to the principal axis must (p. 513) pass through the principal focus F. The intersection of this line with the straight line through C locates the image P' (Fig. 465). Q', the image of Q, is located similarly.

Size of image. Since the image and object are always between the intersecting straight lines PP' and QQ', the triangles PCQ and $P'CQ'$ are similar triangles. We recall from geometry that corresponding lines in similar triangles are proportional. Therefore, since D_o and D_i are the altitudes of triangles PCQ and $P'CQ'$ respectively,

$$\frac{PQ}{P'Q'} = \frac{D_o}{D_i}; \tag{2}$$

that is,

$$\frac{\text{Length of object}}{\text{Length of image}} = \frac{\text{distance of object from lens}}{\text{distance of image from lens}}.$$

From Fig. 465 and equations (1) and (2) we see that

1. When the object is at S, the image is at S', and image and object are of the same size.

2. As the object moves out from S to a great distance, the image moves from S' up to F', becoming smaller and smaller.

3. As the object moves from S up to F, the image moves out to a very great distance to the right, becoming larger and larger.

4. When the object is at F, the emerging waves are plane (the emerging rays are parallel), and no real image is formed.

These four conclusions are represented by the diagrams of Fig. 466. Let these conclusions be tested experimentally by use of the object, lens, and screen of the experiment on page 515.

Virtual image. We have seen that when the object is at F, the waves after passing through the lens are plane. If,

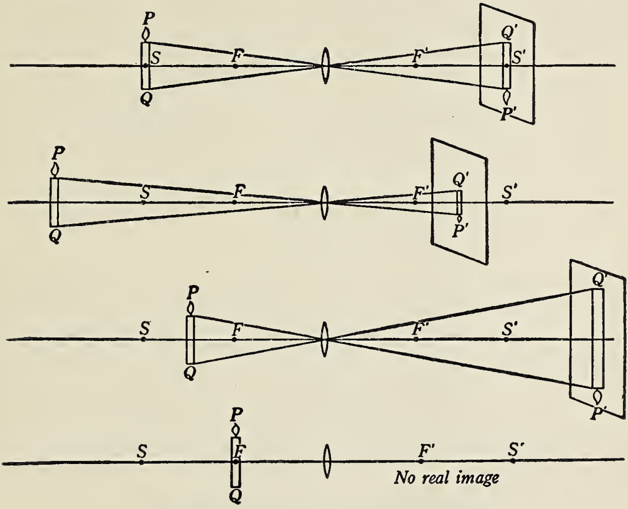


FIG. 466. Relative sizes of image and object

then, the object is nearer to the lens than F, the emerging waves, although reduced in curvature, will still be convex, and, if received by an eye at E, will appear to come from a point P' (Fig. 467). Since, however, no light actually goes from P to P' on its way to the eye, this sort of image is called a *virtual image.* Such an image cannot be projected upon a screen as a real image can, but must be observed by an eye.

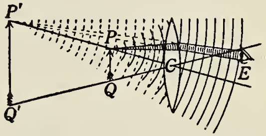


FIG. 467. Virtual image formed by a convex lens

In order to locate a virtual image graphically, we follow exactly the same rules as for a real image. It will be seen that in this case (Figs. 467 and 468) *the image is enlarged and erect.*

Image in concave lens. When a plane wave strikes a concave lens, it must emerge as a divergent wave, since the middle of the wave is retarded by the glass less than the edges (Fig. 469). The point F from which plane waves appear

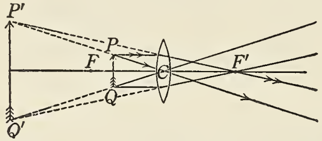


FIG. 468. Ray method of locating a virtual image in a convex lens

FIG. 469. Virtual focus of a concave lens

to come after passing through such a lens is the principal focus of the lens. For the same reason as in the case of the convex lens, the centers of the transmitted waves from P and Q (Fig. 470) — that is, the images P' and Q' — must lie upon the lines PC and QC; and since the curvature is increased by the lens, they must lie closer to the lens than P and Q. Fig. 470 illustrates the way in which such a lens forms an image. This image is always *virtual*, *erect*, and *diminished*. The graphic method of locating the image is shown in Fig. 471.

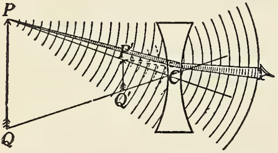


FIG. 470. Image in a concave lens

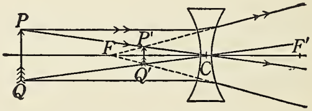


FIG. 471. Ray method of locating an image in a concave lens

Summary. 1. Real images are inverted; virtual images are erect. The length of all images is given by

$$\frac{L_o}{L_i} = \frac{D_o}{D_i},$$

where L_o and L_i denote the length of object and image respectively, and D_o and D_i their distances from the lens or mirror.

2. Convex lenses have a converging effect upon rays (always diminish the curvature of the waves).

a. If the object is *more distant* than the principal focus, *the image is real* and (1) *enlarged* when the object is between the principal focus and twice the focal length; (2) *diminished* when the object is beyond two focal lengths.

b. If the object is less distant than the principal focus, *the image is virtual* and *always enlarged.*

3. Concave lenses have a diverging effect upon the rays (always increase the curvature of the waves). The image is *always virtual* and *diminished* for any position of the object.

4. $$\frac{1}{D_o}+\frac{1}{D_i}=\frac{1}{f}. \qquad \text{(p. 515)}$$

This formula may be applied in all cases, provided that the following points are borne in mind:

a. D_o is always to be taken as positive.

b. D_i is to be taken as positive for real images and negative for virtual images.

c. f is to be taken as positive for converging systems (convex lenses) and negative for diverging systems (concave lenses).

QUESTIONS AND PROBLEMS

A

1. Contrast the effect of convex and concave lenses on parallel rays of light falling on them.

2. What is the difference between a real and a virtual image?

3. Show, by means of a diagram, the relative positions of object, image, and lens in order that a virtual image may be produced by a convex lens.

4. (*a*) When does a convex lens form a real, and when a virtual image? (*b*) When an enlarged, and when a diminished image? (*c*) When an erect, and when an inverted image?

5. (*a*) Describe the image formed by a concave lens. (*b*) Why can it never be larger than the object?

6. Rays diverge from a point 20 cm in front of a converging lens whose focal length is 4 cm. At what point do the rays come to a focus?

7. Copy the following tabulation and, by filling in the blanks, summarize the various images formed by convex lenses. Under "Image Position" should appear "Erect" or "Inverted." Under "Kind of Image" should appear "Real" or "Virtual."

Object Location	Image Location	Image Size	Image Position	Kind of Image
Infinite distance				
Beyond S				
At S				
Between S and F				
Within F				
At F				

B

1. What is the focal length of a lens if the image of an object 10 ft away is 3 ft from the lens?

2. If the object in Problem 1 is 6 in. long, how long will the image be?

3. An object 2 cm long was placed 10 cm from a converging lens, and the image was formed 40 cm from the lens on the other side. Find (*a*) the focal length of the lens and (*b*) the length of the image.

4. At what distance from a convex lens having a focal length of 12 cm must an object be placed in order to form a real image twice as long as the object?

5. Given a convex lens of 18 in. focal length, where should an object be placed to enable the lens to form a real image three times the length of the object?

6. The works of a watch are held 1.5 in. from a jeweler's eye lens which has a focal length of 1.75 in. (*a*) How many inches from the lens is the virtual image formed? (*b*) How many times as great in diameter are the image wheels as the actual wheels?

7. It is desired to enlarge a 2.5 by 4.5 in. photograph to 10 by 18 in. If the distance between the original photograph and the enlarged image is 40 in., what must be the focal length of the lens used?

Images in Mirrors

Image of a point in a plane or a curved mirror. We are all familiar with the fact that to an eye at E (Fig. 472), looking into a plane mirror mn, a pencil point at P appears to be at some point P' behind the mirror. We are able in the laboratory to find experimentally the exact location of this image P' with respect to P and the mirror, but we may also obtain this location from theory as follows: Consider a light wave which originates in the point P (Fig. 472) and spreads in all directions. Let aob be a section of the wave at the instant at which it reaches the reflecting surface mn. An instant later, if there were no reflecting surface, the wave would have reached the position of the dotted line co_1d. Since, however, reflection took place at mn, and since the reflected wave is sent backward with exactly the same velocity with which the original wave would have gone forward, at the proper instant the reflected wave must have reached the position of the line co_2d, so drawn that oo_1 is equal to oo_2. Now the wave co_2d has its center at some point P', and it will be seen that P' must lie just as far below mn as P lies above it, for co_1d and co_2d are arcs of equal circles having the common chord cd. For the same reason, also, P' must lie on the perpendicular drawn from P through mn. When, then, a section of this reflected wave co_2d enters the eye at E, the wave appears to have originated at P' and not at P, for the light actually comes to the eye from P' as a center rather than from P. Hence P' is the image of P. We learn, therefore, that *the image of a point in a plane mirror lies on the perpendicular drawn from the point to the mirror and is as far back of the mirror as the point is in front of it.* This simple rule is sufficient for the interpretation of all the effects found with plane mirrors.

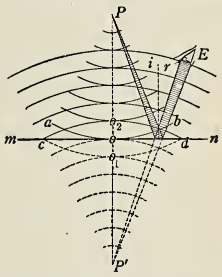


FIG. 472. Wave reflected from a plane surface

Precisely the same construction applied to curved mirrors shows at once (Figs. 473 and 474) that *the image of a point in any mirror, plane or curved, must lie on the perpendicular drawn*

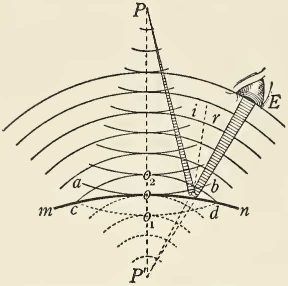


FIG. 473. Wave reflected from a convex surface

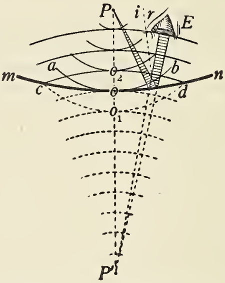


FIG. 474. Wave reflected from a concave surface

from the point to the mirror; but if the mirror is convex, the image is nearer to it than is the point, whereas if it is concave, the image, if formed behind the mirror at all (that is, if it is virtual), is farther from the mirror than is the point.

Construction of image of object in a plane mirror. The image of an object in a plane mirror (Fig. 475) may be located by applying the law proved above for each of its points, that is, *by drawing from each point a perpendicular to the reflecting surface and extending it an equal distance on the other side.*

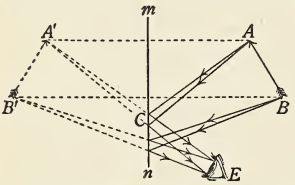


FIG. 475. Construction of image of object in a plane mirror

To find the path of the rays which come from any point of the object, such as A, to an eye placed at E, we have only to draw lines from the image A' of this point to the eye and connect the points of intersection of these lines with the mirror to the original point A. ACE is then the path of the rays. In the same way the path of the rays from B may be traced.

Place a candle (Fig. 476) exactly as far in front of a pane of window glass as a bottle full of water is behind it, both objects being on the same perpendicular drawn through the glass. The candle will appear to be burning inside the water. This explains a large class of familiar optical illusions, such as the "figure suspended in mid-air," the "bust of a person without a trunk," the "stage ghost," etc. In the last case the illusion is produced by causing the audience to look at the actors obliquely through a sheet of very clear plate glass, the edges of which are concealed by draperies. Images of strongly illuminated figures at one side but in front of the glass then appear to the audience to be in the midst of the actors, who are behind the glass.

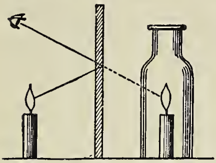


FIG. 476. Position of image in a plane mirror

Focal length of a curved mirror. A curved mirror is usually a portion of a sphere. In this case the center of the sphere, C (Fig. 477), is called the *center of curvature* of the mirror. The line ao passing through this center and the middle of the mirror is called the *principal axis*. A pair of rays like ao and bo' parallel to the principal axis are brought together at a point F that is called the *principal focus* of the mirror. The distance of this focus from the mirror is in fact very close to half the distance of the center of curvature, so that the focal length of any spherical mirror is usually taken as half its radius of curvature.

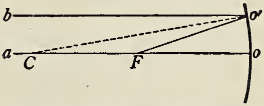


FIG. 477. The concave mirror

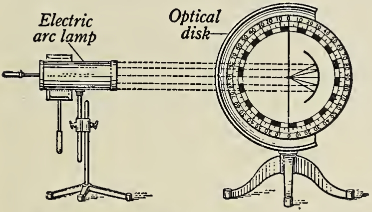


FIG. 478. Concave mirror converges parallel rays

Actually there is no single meeting point of *all* the parallel rays meeting a spherical mirror. This failure is known as *spherical aberration*. It is not serious for small mirrors, but

how serious it is for large ones is illustrated in Fig. 479. A mirror of parabolic form, however, has the property of bringing all rays arriving parallel to its principal axis to an exact focus, or, conversely, of causing all rays emitted from a point

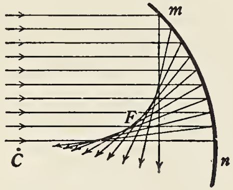


FIG. 479. Spherical aberration in mirrors

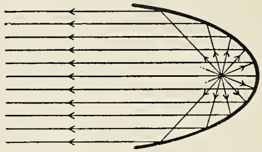


FIG. 480. A mirror corrected for spherical aberration

placed at its principal focus to leave the mirror as an exactly parallel beam. This is why a searchlight mirror is always given a parabolic shape (Fig. 480). Likewise the mirror of the 200-inch reflecting telescope at the California Institute of Technology is as nearly as possible a perfect parabola.

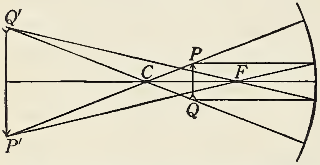
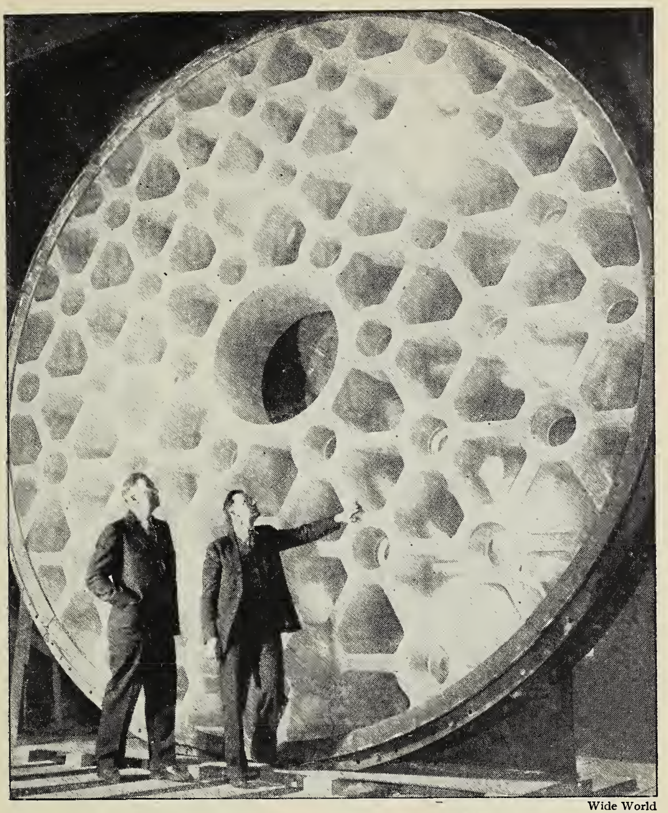


FIG. 481. Ray method of locating real image in a concave mirror

Images in concave mirrors. The position of an image formed by a concave mirror may be determined geometrically in just the same way as the position of an image formed by a convex lens. The ray from P (Fig. 481) parallel to the axis of the mirror must pass through F after reflection. The ray from P passing through C strikes the surface of the mirror at right angles and is thus reflected back upon itself. The intersection of these two rays locates P'. Verify with a candle and a concave mirror, as in Fig. 482, the following results:

1. When the object is between the mirror and the principal focus, the image is virtual, erect, enlarged, and lies behind the mirror.



Wide World

The World's Largest Astronomical Mirror

The 17-ton pyrex-glass casting from which the world's largest astronomical mirror is being made in the shops of the California Institute of Technology. This shows the ribbed structure of the back of the mirror, the opposite face of which will finally be a paraboloid. The casting is 200 inches in diameter and 24 inches thick. If this mirror performs as calculated, it will bring into view 27 times the volume of space now accessible to the next largest telescope, which has a diameter of 100 inches. The gain in light-concentrating power is due not only to the much greater area of the new mirror but also to its shorter relative focal length

Section of a Motion-Picture Film Showing Newton D. Baker Turning his Head to Speak to General Pershing

The motion-picture camera makes a series of snapshots upon a film, usually at the rate of 16 per second. The film is drawn past the lens with a jerky movement, being held at rest during the instant of exposure and moved forward while the shutter is closed. The pictures are $\frac{3}{4}$ inch high and 1 inch wide. A reel of film 1000 feet long (the usual length) thus contains 16,000 pictures. From the reel of negatives a reel of positives is printed for use in the projection apparatus. The optical illusion of "moving" pictures is made possible by a peculiarity of the eye called persistence of vision. To illustrate this, whirl a firebrand rapidly in a circle. The spot of light appears drawn into an arc. This is due to the fact that we continue to see an object for a small fraction of a second after the image of it disappears from the retina. The period of time varies somewhat with different individuals. The so-called "moving" pictures do not move at all. In normal projection 16 brilliant stationary pictures per second appear in succession upon the screen, and during the interval between the pictures the screen is perfectly dark. It is during this period of darkness that the film is jerked forward to get the next picture into position for projection. The eye, however, detects no period of darkness, for on account of persistence of vision it continues to see the stationary picture not only during this period of darkness but dimly for an instant even after the next picture appears upon the screen. This causes the successive stationary pictures, which differ but slightly, to blend smoothly into one another and thus give the effect of actual motion

2. When it is at the focus, the reflected waves are plane; that is, all the rays from a point are reflected parallel to the axis. Therefore there is no image formed.

3. When it is between the principal focus and the center of curvature, the image is real, inverted, enlarged, and beyond the center of curvature C.

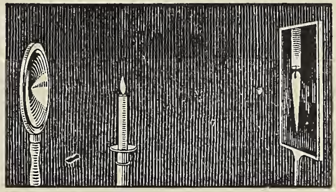


FIG. 482. Real image of candle formed by a concave mirror

4 When it is at the center of curvature, the image is real, inverted, the same size, and likewise at C.

5. When it is farther from the mirror than C, the image is real, inverted, diminished, and between C and F. When the object is very far away, the rays coming to the mirror are nearly parallel, and the image will be found practically at the focus. This is the most convenient way of finding the focal length.

It is apparent from a study of these properties that they are exactly like those of a convex lens. This is because, like the convex lens, the concave mirror *always diminishes the curvature of the waves striking it by $1/f$.* The same formulas hold throughout, and the same constructions are applicable.

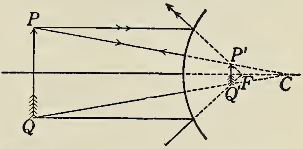


FIG. 483. Image in a convex mirror

Image of an object in a convex mirror. We are all familiar with the fact that a convex mirror always forms behind the mirror a virtual, erect, and diminished image. The reason for this is shown clearly in Fig. 483. The image of the point P lies, as in plane mirrors (p. 521), always on the perpendicular to the mirror, but now necessarily nearer to the mirror than the focus F, since, as the point P is moved from a position very close to the mirror, where its image is just behind it, out to an infinite distance, its image moves back only to the focal

plane through F. Hence the image must lie somewhere between F and the mirror. The image $P'Q'$ of an object PQ is always diminished, because it lies between the converging lines PC and QC. It can be located by the ray method (Fig. 483) exactly as in the case of concave lenses. In fact, a convex mirror and a concave lens have exactly the same optical properties. This is because *each always increases the curvature of the incident waves by an amount $1/f$.*

Summary. **Concave mirrors and convex lenses have the same optical properties. (See summary, pp. 518, 519.)**

Convex mirrors and concave lenses have the same optical properties. (See summary, p. 519.)

QUESTIONS AND PROBLEMS

A

1. Describe the image formed by a plane mirror.

2. Show by a diagram why the images of trees on the opposite side of a still lake appear inverted in the water.

3. A man is standing squarely in front of a plane mirror which is very much taller than he is. The mirror is tipped toward him until it makes an angle of 45° with the horizontal. He still sees his full length. What position does his image occupy?

4. Contrast the effect of convex and concave mirrors on parallel rays of light.

5. (*a*) Describe the image formed by a convex mirror. (*b*) Why can it never be larger than the object?

6. (*a*) When does a concave mirror form a real image? (*b*) a virtual image? (*c*) When an enlarged image? (*d*) a diminished image? (*e*) When an erect image? (*f*) an inverted image?

B

1. (*a*) Show from a construction of the image that a man cannot see his entire length in a vertical mirror unless the mirror is half as tall as he is. (*b*) Decide from a study of the figure whether or not the distance of the man from the mirror affects the case.

2. Can a convex mirror ever form an inverted image? Why?

3. Why does the nose appear relatively large in comparison with the ears when the face is viewed in a convex mirror?

4. An object 5 cm long is 50 cm from a concave mirror of focal length 30 cm. Where is the image, and what is its size?

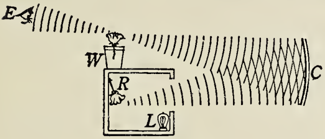


FIG. 484

5. A candle placed 20 cm in front of a concave mirror has its image formed 50 cm in front of the mirror. Find the radius of the mirror.

6. If a rose R is pinned upside down in a brightly illuminated box, a real image may be formed in a glass of water W by a concave mirror C (Fig. 484). Where must the eye be placed to see the image?

7. How far is the rose from the mirror in the arrangement of Fig. 484?

Optical Instruments

The photographic camera. Copernicus, Galileo, and other early astronomers had of course none of our modern instruments with which to observe the heavens. They found, however, that if they placed a screen behind a little hole in the wall of a darkened room, they could get images of eclipses of the sun and other astronomical events. The principle is the same as in the pinhole camera, which consists merely of a small box with a pinhole in one side and a photographic plate against the other (Fig. 485). Since light travels in straight lines, there is an image of a_1 at a'_1, of a_2 at a'_2, and so on. The trouble with the pinhole camera is that it does not let in enough light. If we try to make the image brighter by enlarging the hole, the image becomes blurred, because the narrow pencils $a_1a'_1$, $a_2a'_2$, etc. become cones whose bases a'_1, a'_2, overlap and thus destroy the distinctness of the outline.

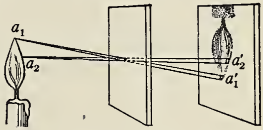


FIG. 485. Image formed by a small opening

It is possible, without sacrificing distinctness of outline, to gain the increased brightness due to the larger hole by placing a lens in the hole (Fig. 486). The apparatus then becomes a photographic camera. But whereas with the pinhole camera the screen may be at any distance from the hole, with a lens the plate and the object must be at conjugate foci of the lens.

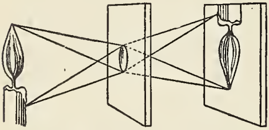


FIG. 486. Principle of the photographic camera

Place a lens of say 4 ft focal length in front of a hole in the shutter of a darkened room, and place a semitransparent screen (for example, architect's tracing paper) at the focal plane. A perfect reproduction of the opposite landscape will appear. A common type of camera is shown in Fig. 487.

The projecting lantern. The projecting lantern is essentially a camera in which the position of object and image have been interchanged; for in the use of the camera the object is at a considerable distance, and a small inverted image is formed on a plate or film placed just beyond the focal point. In the use of the projecting lantern the object P (Fig. 488) is placed just beyond the focal point of the lens L', and an enlarged inverted image is formed on a distant screen S. In both these instruments the optical part is a combination of lenses which is the equivalent of a convex lens.

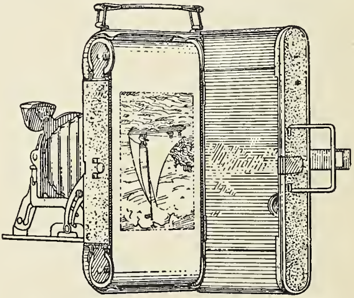


FIG. 487. The photographic camera

The object P, whose image is formed on the screen, is usually a transparent slide which is illuminated by a powerful light A. The image is as many times as large as the object as the distance from L' to S is greater than the distance from

L' to P. The light A is usually either an incandescent lamp or an electric arc. The motion-picture projector employs a long film of small "positives" which moves swiftly between the condensing lens L and the projecting lens L'. (See opposite page 525.)

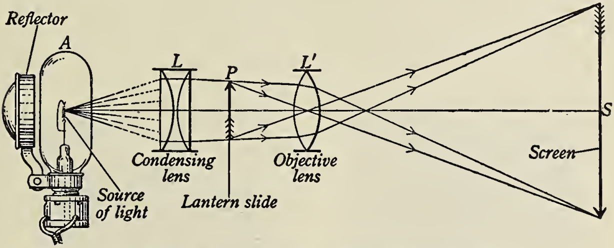


FIG. 488. The projecting lantern (stereopticon)

The description above includes only the essential parts of a projecting lantern. In order that the slide may be illuminated as brilliantly as possible, however, a so-called condensing lens L is always used. This concentrates light upon the transparency and directs it toward the screen.

In order to illustrate the principle of the instrument, let a beam of sunlight be reflected into the room and fall upon a lantern slide. When a lens is placed a trifle more than its focal distance in front of the slide, a brilliant picture will be formed on the opposite wall.

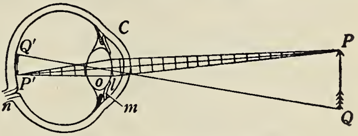


FIG. 489. The human eye

The eye. The eye is essentially a camera in which the *cornea* C (Fig. 489), the *aqueous humor* l, and the *crystalline lens* o act as one single lens which forms an inverted image $P'Q'$ on the *retina*, an expansion of the optic nerve n covering the inside of the back of the eyeball. It differs from the camera, however, in its method of focusing.

In the case of the camera the images of objects at different distances are obtained by placing the lens nearer to the film or farther from it. In the eye, however, the distance from the retina to the lens remains constant, and the adjustment for different distances is brought about by changing the focal length of the lens system in such a way as always to keep the image upon the retina. Thus, when the normal eye is perfectly relaxed, the lens has just the proper curvature to focus plane waves upon the retina, that is, to make distant objects

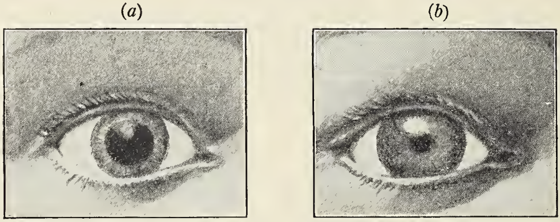


FIG. 490. The pupil, or opening in the iris, opens out when the light is dim and contracts when it is intense

distinctly visible. But by directing attention upon objects close by we cause the muscles which hold the lens in place to contract in such a way as to make the lens more convex, and thus bring into distinct focus objects which may be as close as 8 or 10 inches. This power of adjustment, or *accommodation*, however, varies greatly in different individuals.

The *iris*, *m* (Fig. 489), or colored part of the eye, is a diaphragm which varies the amount of light which is admitted to the retina (Fig. 490 (*a*) and (*b*)).

Nearsightedness and farsightedness. In a *normal* eye, provided the lens is relaxed and resting, parallel rays come to a focus *on* the retina (Fig. 491 (*a*)); in a *nearsighted* eye they focus *in front of* the retina (Fig. 491 (*b*)); and in a *farsighted* eye they reach the retina *before coming to a focus* (Fig. 491 (*c*)).

Those who are nearsighted can see distinctly only those objects which are near. The usual reason for nearsightedness

is that the retina is too far from the lens. Glasses with concave, or diverging, lenses correct this defect of vision because they make the rays from a distant object enter the eye as if they had come from an object near by; that is, they partially counteract the converging effect of the eye (Fig. 491 (*b*)).

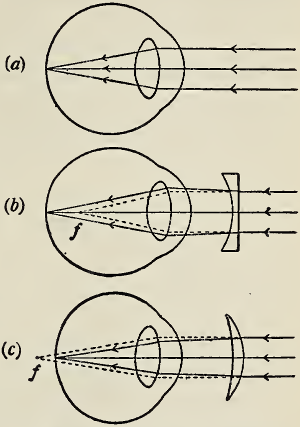


FIG. 491. Defects of vision

Those who are farsighted cannot see distinctly even a very distant object *when the lens is relaxed*. The usual reason for farsightedness is that the eyeball is too short from lens to retina. The rays from *near* objects are converged, or focused, towards *f* behind the retina in spite of all effort at accommodation. Glasses with convex, or converging, lenses give distinct vision because they supplement the converging effect of the eye (Fig. 491 (*c*)). In old age the lens loses its power of accommodation, that is, the ability to become more convex when looking at a near object; hence in old age a normal eye requires for near objects the same lens as is used in true farsightedness.

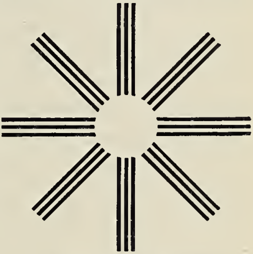


FIG. 492. Astigmatism

Astigmatism. Sometimes the cornea of the eye is not spherical. The curvature of a vertical arc, for example, is different from that of a horizontal arc. This defect is called astigmatism. To a person with astigmatism the lines in Fig. 492 will not appear equally clear and black. Lenses specially ground to correct this defect are used. The correction may be combined with one for nearsightedness or farsightedness.

The apparent size of a body. The apparent size of a body depends simply upon the size of the image formed upon the retina by the lens of the eye, and hence upon the size of the *visual angle pCq* (Fig. 493). The size of this angle evidently increases (*PCQ*) as the object is brought nearer to the eye. Thus the image formed on the retina when a man is 100 feet from the eye is in reality only one tenth as large as the image formed of the same man when he is but 10 feet away. We do not actually interpret the larger image as representing a larger man, simply because we have been taught by lifelong experience to take account of the known distance of an object in forming our estimate of its actual size. To an infant who has not yet formed ideas of distance the man 10 feet away doubtless appears ten times as large as the man 100 feet away.

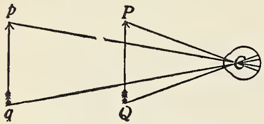


Fig. 493. The visual angle

Distance of most distinct vision. When we wish to examine an object minutely, we bring it as close to the eye as possible in order to increase the size of the image on the retina. But there is a limit to the size of the image which can be produced in this way; for when the object is brought nearer to the normal eye than about 10 inches, the curvature of the incident wave becomes so great that the eye lens is no longer able, without too much strain, to thicken sufficiently to bring the image into sharp focus upon the retina. Hence a person with normal eyes holds an object which he wishes to see as distinctly as possible at a distance of about 10 inches.

Although this so-called *distance of most distinct vision* varies somewhat with different people, for the sake of having a standard of comparison in the determination of the magnifying powers of optical instruments some exact distance had to be chosen. The distance so chosen is 10 inches, or 25 centimeters.

Magnifying power of a convex lens. If a convex lens is placed just in front of the eye, the object may be brought much closer than 25 centimeters without loss of distinctness,

for the extreme curvature of the wave is largely or even wholly overcome by the lens before the light enters the eye.

If we wish to use a lens as a magnifying glass to the best advantage, we place the eye *as close to it as we can*, so as to gather as large a cone of rays as possible, and then place the object at or very close to the principal focus, so that the waves after passing through it are practically plane. They are then focused by the eye with the least possible effort. The visual angle in such a case is PcQ (Fig. 494 (a)). If the object is placed just a trifle inside of the focus so that the image $P'Q'$ is at 25 centimeters, the distance of most distinct vision, as shown in the figure, this visual angle will not be appreciably different, since the image must always lie between the lines $P'c$ and $Q'c$. If, however, the lens were not present, and if the object itself, pq, were 25 centimeters from the eye, the visual angle would be the small angle pcq (Fig. 494 (b)). *The magnifying power of a simple lens is due, therefore, to the fact that by its use an object can be viewed distinctly when held closer to the eye than is otherwise possible. This condition gives a visual angle that increases the size of the image on the retina.* The less the focal length of the lens, the nearer to it may the object be placed, and therefore the greater the visual angle, or magnifying power.

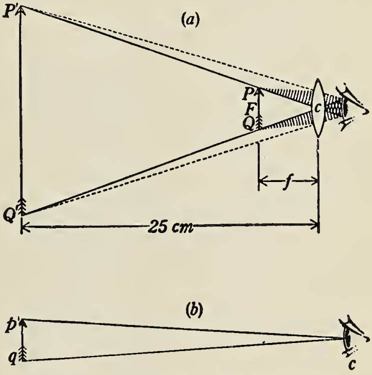


FIG. 494. Magnifying power of a lens

It can be shown by geometry that the ratio of the two angles PcQ and pcq is approximately $25/f$, where f is the focal length of the lens expressed in centimeters. Now *the magnifying power of a lens or microscope is defined as the ratio of the*

angle actually subtended by the image when viewed through the instrument, to the angle subtended by the object when viewed with the unaided eye at a distance of 25 centimeters. Therefore the magnifying power of a simple lens is $25/f$. Thus, if a lens has a focal length of 2.5 centimeters, it produces a magnification of 10 diameters when the object is placed at its principal focus. If the lens has a focal length of 1 centimeter, its magnifying power is 25, etc.

The telescope. The telescope, another application of the simple principle of refraction, has made possible most of our knowledge of the heavens by bringing out details not visible to the naked eye. In the astronomical telescope the *objective* o, Fig. 495, or forward lens, forms an image $P'Q'$ of an object PQ, usually so far away that the image is for all practical purposes formed at the principal focus of the lens. This image may be viewed by the unaided eye at a distance of 25 centimeters.

[The magnifying power of the objective lens is due to the fact that it increases the visual angle, and it is measured by

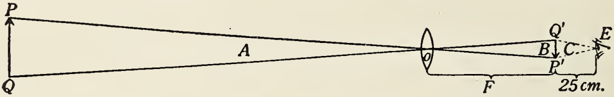


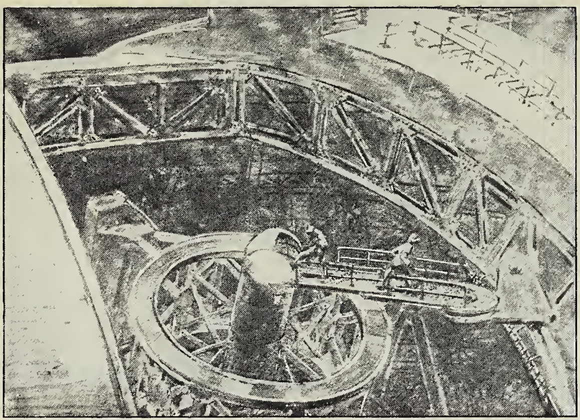
FIG. 495. The magnifying power of a telescope objective is $F/25$

that increase. Seen with the naked eye, the visual angle of the object is A (Fig. 495). The visual angle of the image, however, viewed at the ideal distance of 25 centimeters, is C. It can be proved by geometry that the ratio of these angles, or the magnifying power of the lens, is approximately equal to the focal length of the objective divided by 25, that is, $F/25$.*

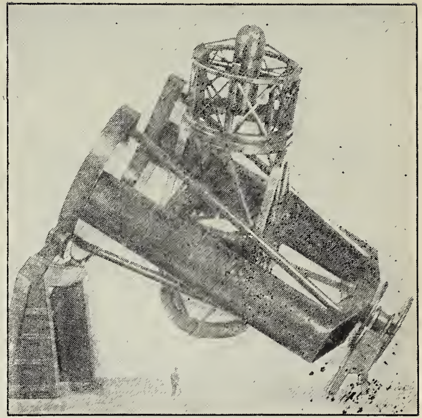
[In practice the real image $P'Q'$ is not viewed with the naked eye but is further magnified with a simple short-focus mag-

* For $A = B$. Regarding $P'Q'$ as an arc we see that angles C and B ($= A$) are inversely proportional to their radii; that is,

$$\frac{\text{Visual angle of image}}{\text{Visual angle of object}} = \frac{C}{A} = \frac{C}{B} = \frac{F}{25}.$$



Changing Observers at the Principal Focus of the 200-Inch Telescope



Model of the 200-Inch Telescope

The 200-inch (17-foot) mirror is carried in the bottom end of the telescope tube as is shown in the figure at the right. This tube, which is of exceeding rigidity, is 20 feet in diameter, 60 feet long, and weighs 125 tons. It moves automatically and with great precision so as to keep the image or spectrum of the star being studied on the photographic plate throughout the night, as this star sweeps across the heavens from the eastern horizon to the western horizon. By means of suitable reflections from mirrors the light of a star can be brought to a focus in three different observation chambers. In the chamber at the principal focus, which is situated within the cartridge-shaped house at the upper end, as shown in the figures, the supports carrying the observer and his instruments are geared to the moving tube in such a manner that he is entirely unconscious of any motion, since the supports always maintain the same position with respect to the vertical. The entire telescope stands within a dome measuring 135 feet in diameter

A Spiral Nebula

One of the objects for the study of which the 200-inch telescope is peculiarly adapted because of its very large light-concentrating power. The spiral nebula nearest to our own galaxy, known as the great nebula in Andromeda, is 1,000,000 light years away, and others are known to be a hundred times more remote. The stellar system in which our earth is situated is thought to be merely such a spiral nebula, the Milky Way outlining the plane of the spiral

nifying glass called an *eyepiece* (Fig. 496) placed so that the image is at its focus.

[Since we have seen (p. 534) that the simple magnifying glass increases the visual angle $25/f$ times, f being the focal length of the eyepiece, it is clear that the total magnification produced by both lenses, used as above, is $F/25 \times 25/f = F/f$. *The magnifying power of an astronomical telescope is therefore the focal length of the objective divided by the focal length of the eyepiece.* It will be seen, therefore, that to get a high magnifying power it is necessary to use an objective of as great focal length as possible and an eyepiece of as short focal length as possible. The focal length of the lens at the Yerkes Observatory is about 62 feet, and its diameter 40 inches. The great diameter enables it to collect a very large amount of light, which makes celestial objects more plainly visible.

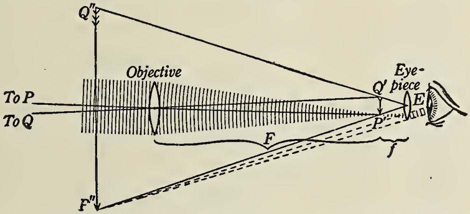


FIG. 496. The magnifying power of a telescope is F/f

[Eyepieces often have focal lengths as small as $\frac{1}{4}$ inch. Thus the Yerkes telescope, when used with a $\frac{1}{4}$-inch eyepiece, has a magnifying power of 2976.

[The largest telescopes are *reflecting* rather than refracting. The image is formed by a mirror instead of a lens, the principle being otherwise just the same. In practice it has never been found feasible to build refractors larger than 40 inches in diameter, whereas mirrors as large as 200 inches in diameter have been constructed.

[For viewing objects on the earth the terrestrial telescope is used. This differs from the astronomical telescope only in

that an extra convex lens is inserted to invert the image so that it will not be upside down. Such telescopes are used at sea (spyglasses) and extensively in surveying and in range-finding for artillery.

[**The magnifying power of the compound microscope.** The major portion of the sciences of biology and medicine could never have been developed had the principle of refraction not been discovered and applied in the compound microscope, which enables us to see such very small objects as minute living cells and disease germs. This instrument is like the telescope in that the front lens, or *objective*, forms a real image of the object at the focus of the eyepiece. The size of the image $P'Q'$ (Fig. 497) formed by the objective is as many times the size of the object PQ as D_i, the distance from the objective to the image, is times D_o, the distance from the objective to the object (p. 516). Since the eyepiece magnifies this image $25/f$ times, the total magnifying power of a compound microscope is $D_i/D_o \times 25/f$. Ordinarily D_i is practically the length L of the microscope tube, and D_o is the focal length F of the objective. Wherever this is the case, then, the magnifying power of the compound microscope is $25\ L/Ff$.

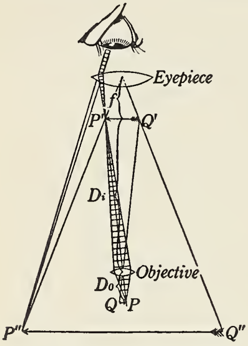


FIG. 497. The compound microscope

[The relation shows that in order to get a high magnifying power with a compound microscope the focal length of both eyepiece and objective should be as short as possible, whereas the tube length should be as long as possible. Thus, if a microscope has both an eyepiece and an objective of 6 millimeters focal length and a tube 15 centimeters long, its magnifying power will be

$$\frac{25 \times 15}{.6 \times .6} = 1042.$$

Magnifications as high as 2500 or 3000 are sometimes used, but it is impossible to go much farther, for the reason that the image becomes too faint to be seen when it is spread over so large an area.

The opera glass. On account of the large number of lenses which must be used in a terrestrial telescope, it is too bulky and awkward for many purposes, and hence it is often replaced by the opera glass (Fig. 498). This instrument consists of an objective like that of the telescope, and an eyepiece which is a concave lens of the same focal length as the eye of the observer. The effect of the eyepiece is therefore to neutralize the lens of the eye. Hence the objective, in effect, forms its image directly upon the retina. This means that the angle of vision $P'cQ'$ ($= P''cQ''$) obtained through the use of the opera glass is as many times the angle of vision PCQ ($= P''CQ''$) for the unaided eye as the focal length CR of the objective is times the focal length cR of the eye; that is, the size of the image formed upon the retina *by the objective* is as many times as large as that formed *by the unaided eye* as CR is times cR. Since the focal length of the eye is the same as that of the eyepiece, *the magnifying power of the opera glass, like that of the astronomical telescope, is the ratio of the focal lengths of the objective and eyepiece.* Objects seen with an opera glass appear erect, since the image formed on the retina is inverted, as is the case with images formed by the lens of the eye unaided.

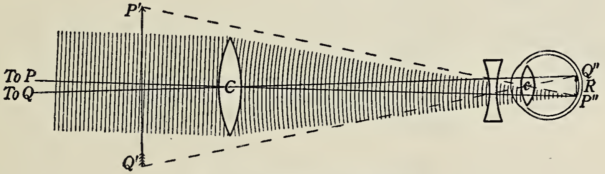


FIG. 498. The opera glass

The prism binocular. The greatest disadvantage of the opera glass is that the field of view is very small. The terres-

trial telescope has a larger field but is of inconvenient length. An instrument called the prism binocular (Fig. 499) combines the compactness of the opera glass with the wide field of view of the terrestrial telescope. The compactness is gained by causing the light to pass back and forth through total-reflecting prisms, as in the figure. These reflections also perform the function of reinverting the image, so that the real image, which is formed at the focus of the eyepiece, is erect. It will be seen, therefore, that the instrument is essentially an astronomical telescope in which the image is reinverted by reflection and in which the tube is shortened by letting the light pass back and forth between the prisms.

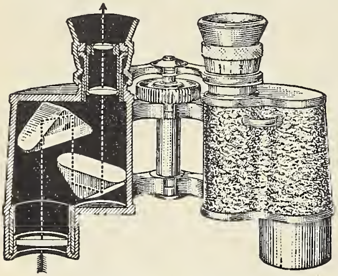


FIG. 499. The prism binocular

Summary. The camera, the projection lantern, and the eye form real images on screens.

The magnifying power of the microscope, the telescope, the opera glass, and the field glass is due to the increase they produce in the visual angle.

The magnifying power of a single lens is considered equal to the ratio of 25 centimeters (or 10 inches) to the focal length of the lens.

The magnifying power of the telescope and of the opera glass is equal to the ratio of the focal length of the objective to that of the eyepiece.

The magnifying power of a compound microscope is the product of the magnifying power of the objective and that of the eyepiece.

QUESTIONS AND PROBLEMS

A

1. If a pinhole camera is 8 in. long and the image of a building 50 ft high appears as an image 3 in. high on the plate, how far away is the building?

2. (*a*) When a camera is adjusted to photograph a distant object, what change in the length of the bellows must be made to photograph a near object? (*b*) Explain clearly why this adjustment is necessary.

3. Is the image on the retina erect or inverted?

4. (*a*) Why is it necessary for the pupils of your eyes to be larger in a dim cellar than in the sunshine? (*b*) Why does the photographer use a large stop on dull days in photographing moving objects?

5. What sort of lenses are necessary to correct (*a*) nearsightedness? (*b*) farsightedness? (*c*) Explain with the aid of a diagram.

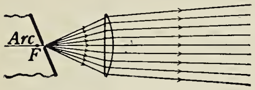


FIG. 500. Principle of the spotlight

6. Fig. 500 represents a theater spotlight projector adjusted to illuminate a small part of the stage. How must the arc be moved to illuminate a larger area on the stage? (*F* is the principal focus of the plano-convex lens.)

7. The image, on the retina, of a book held 1 ft from the eye is larger than that of a house on the opposite side of the street. Why do we not judge that the book is actually larger than the house?

8. Explain how a telescope forms the image that you see when you look through it.

9. (*a*) What should be the focal length of the lens of a camera designed to photograph distant objects on a film 6 in. behind the lens? (*b*) How far from the film should this lens be placed to focus properly an object distant 10 in. from the lens?

B

1. How tall is a tree 200 ft away if the image of it formed by a camera lens of focal length 4 in. is 1 in. long? (Consider the image to be formed in the *focal plane.*)

2. How long an image of the same tree will be formed in the focal plane of a lens having a focal length of 9 in.?

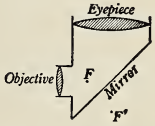


FIG. 501. View-finder of camera

3. From Fig. 501 explain the camera view-finder, *F* being the principal focus of the objective and *F′* that of the eyepiece.

4. A telescope has an objective whose focal length is 30 ft and an eyepiece whose focal length is 1 in. What is the magnifying power of the telescope?

5. Given a spectacle lens, how could you determine whether it is a converging or a diverging lens?

6. What is the magnifying power of a $\frac{1}{4}$-inch lens used as a simple magnifier?

7. A child 3 ft in height stood 15 ft from a camera whose lens had a focal length of 18 in. What was (*a*) the distance from the lens to the photographic plate and (*b*) the length of the child's photograph?

8. A compound microscope has a tube length of 8 in., an objective of focal length $\frac{1}{2}$ in., and an eyepiece of focal length 1 in. What is its magnifying power?

9. If the focal length of the eye is 1 in., what is the magnifying power of an opera glass whose objective has a focal length of 4 in.?

10. The parabolic mirror used as an objective in one of the telescopes at the Mt. Wilson Observatory is 100 in. in diameter and has a focal length of about 50 ft. What magnification is obtained when it is used (*a*) with a 2-inch eyepiece; (*b*) with a 1-inch eyepiece? (*c*) What is gained by the use of a mirror of such enormous diameter?

11. Explain why both near and distant objects can be satisfactorily photographed with a small fixed-focus camera.

12. The projection lens of a lantern has a focal length of 1 ft. How far behind the lens must a slide be placed in order to focus clearly upon a screen 24 ft from the lantern?

Color Phenomena

Color and Wave Lengths

Wave lengths of different colors. Often when we look at clear cut glass or at films of oil or soap from certain angles we see many colors. Perhaps if we examine this phenomenon of the breaking up of white light into color more closely, we can learn something about the nature of color.

Dip a clean wire ring into a clean soap solution so as to form a film across the ring. Let a beam of sunlight or the light from a projection lantern pass through a piece of red glass at *A*, fall upon the soap film held vertical at *F*, and be reflected from it to a white screen *S* (Fig. 502). Further, place a convex lens in the path of the beam in such a position that it will form an image of the film on the screen *S*. Now the water in the film will run toward the bottom, making it wedge-shaped. The system of red and black bands upon the screen is formed by the interference of the two beams of light reflected from the front and back of this wedge-shaped film. Now hold the red glass in one half of the beam and a piece of green glass in the other half, the two pieces being placed edge to edge, as shown at *A*. Two sets of fringes will be seen side by side on the screen. The fringes will be red and black on one side of the image, and green and black on the other; but it will be noticed at once that the dark bands on the green side are closer together than the dark

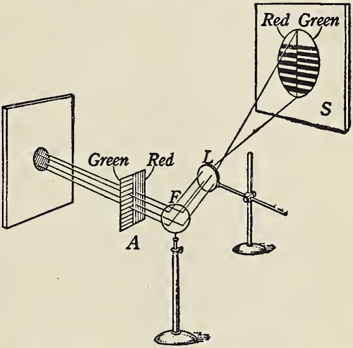


FIG. 502. Projection of soap-film fringes

bands on the other side; in fact, seven fringes on the side of the film which is covered by the green glass will be seen to cover about the same distance as six fringes on the red side.*

It was shown in Fig. 441 that the distance between two dark bands corresponds to an increase of half a wave length in the thickness of the film. Therefore, since the dark bands on the red side are farther apart than those on the green side, red light must have a longer wave length than green light. Similarly, by using glass of other colors, we can show that each color has a distinctive wave length. The wave length, number of waves per centimeter, and rate of vibration of the *central portion* of each colored region of the spectrum are roughly as follows:

Color	Wave Length in Centimeters	Number of Waves per Centimeter	Number of Waves per Second (Frequency)
Violet	.000041	24,400	732,000,000,000,000
Indigo	.000043	23,300	698,000,000,000,000
Blue	.000047	21,300	639,000,000,000,000
Green	.000052	19,200	576,000,000,000,000
Yellow	.000057	17,500	525,000,000,000,000
Orange	.000062	16,100	483,000,000,000,000
Red	.000071	14,100	423,000,000,000,000

Remove the red and green glasses from the path of the beam. The red and green fringes will be seen to be replaced by a series of bands brilliantly colored in different hues. These are due to the fact that the lights of different wave length form interference bands at different places on the screen. Notice that the upper edges of the bands (lower edges in the inverted image) are reddish, whereas the lower edges are bluish. We shall find the explanation of this fact on page 547.

Composite nature of white light shown by dispersion. Newton studied color in another way by means of a prism. This is a very beautiful way of investigating the nature of white light.

* The experiment may be performed at home by simply looking through red and green glasses at a soap film so placed as to reflect white light to the eye.

Let a beam of sunlight pass through a narrow slit and fall on a prism, as in Fig. 503. The beam which enters the prism as white light is dispersed into red, yellow, green, blue, and violet lights, although each color gradually merges into the next. This band of color is called a *spectrum.*

We conclude from this experiment that *white light is a mixture of all the colors of the spectrum, from red to violet inclusive.* Examine the spectrum. Which is refracted more, the red light or the green?

Thus it is clear that light of *long* wave length suffers less refraction than that of *short* wave length. This effect is called *dispersion.* The spectrum is, then, an arrangement of colors in the order of their wave lengths.

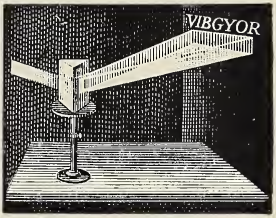


FIG. 503. White light dispersed by a prism

Color of bodies. Pass a beam of white light through a prism to produce a spectrum. Place a skein of pure red yarn in various portions of the spectrum. It will appear nearly black everywhere except in the red portion. Similarly a skein which in white light is blue will appear nearly black in every portion of the spectrum except the blue portion, where it will take on its blue color.

This experiment suggests the conclusion that bodies are colored simply because they are able to reflect only certain wave lengths of light. When white light, containing all wave lengths, falls on a red body, the body reflects only the red wave lengths, absorbing all the rest. When blue light alone falls on a red body, it reflects little or none of the light, and thus appears black. When red light falls on a red body it reflects the light strongly, appearing red. Bodies are called black which reflect little or no light, absorbing all wave lengths. White bodies are bodies which reflect some light of all wave lengths.

To prove this place a white body in various parts of the spectrum. It appears red in the red, blue in the blue, etc.

To investigate transparent bodies, such as colored glass and the like, pass a beam of white light through a piece of red glass. It absorbs all wave lengths but the red, transmitting a red beam. Substitute green glass for the red. All colors are absorbed but the green, which is transmitted. Now place the red glass in the white beam and the green glass in the red beam thus produced. Nothing is transmitted through the green glass, because no green light falls upon it but only red, which is almost entirely absorbed.

To sum up, the color of bodies depends on two things: (1) the light which falls upon them and (2) the light which they are capable of reflecting or transmitting. The color of an *opaque* object depends on the wave length of the light it *reflects*, that of a *transparent* object on the wave length of the light it *transmits*.

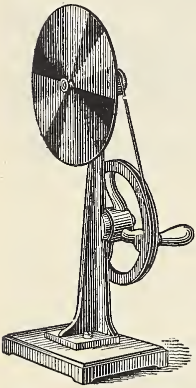


FIG. 504. Newton's color disk

Compound colors. The student must not get the idea from the preceding paragraphs that every color except white has one definite wave length, for the same effect may be produced on the eye by a mixture of several different wave lengths as is produced by a single wave length. This statement may be proved by the use of an apparatus known as Newton's color disk (Fig. 504). The arrangement makes it possible to rotate differently colored sectors so rapidly before the eye that the effect is exactly the same as though the colors came to the eye simultaneously. If one half of the disk is red and the other half green, the rotating disk will appear yellow, the color being very similar to the yellow of the spectrum. If green and violet are mixed in the same way, the result will be light blue. Although the colors produced in this way are not distinguishable by the eye from spectral colors, it is obvious that their physical constitution is wholly different; for whereas a spectral color consists of waves of a single wave length, the colors produced by mixture are compounds of

several wave lengths. For this reason the spectral colors are called pure and the others compound. In order to tell whether the color of an object is pure or compound, it is only necessary to observe it through a prism. If it is compound, the colors will be separated, giving an image of the object for each color. If it is pure, the object will appear through the prism exactly as it does without the prism.

By compounding colors in the way described above we can produce many which are not found in the spectrum. Thus mixtures of red and blue give purple or crimson; mixtures of black with red, orange, or yellow give rise to the various shades of brown. Lavender may be formed by adding seven parts of white to eight of blue and one of red; lilac, by adding two parts of white to one part of red and three parts of blue; olive, by adding one part of black to two parts of green and one of red.

Complementary colors. Since white light is a combination of all the colors from red to violet inclusive, it might be expected that if one or several of these colors were subtracted from white light, colored light would be left.

To test this experimentally pass a beam of sunlight through a slit *s*, a prism *P*, and a lens *L*, to a screen *S*, arranged as in Fig. 505. A spectrum will be formed at *RV*, the position conjugate to the slit *s*, and a pure white spot will appear on the screen when it is at the position which is conjugate to the prism face *ab*. Slip a card into the path of the beam at *R*, so as to cut off the red portion of the light. The spot on *S* will appear a brilliant shade of greenish blue. This is the compound color left after red is taken from the white light. This shade of blue is therefore called the *complementary color* of the red which has been subtracted. Two *complementary colors* are such as produce white when added together.

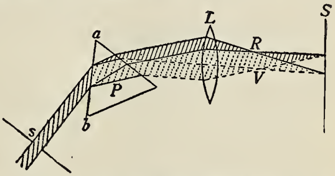


FIG. 505. Recombination of spectral colors into white light

Slip the card in from the side of the blue rays at *V*. The spot will first take on a yellowish tint when the violet alone is cut out; and as the card is slipped farther in, the image will become a deep shade of red when violet, blue, and part of the green are cut out.

Next hold a lead pencil vertically between R and V so as to cut off the middle part of the spectrum, that is, the yellow and green rays. The remaining red, blue, and violet will unite to form a brilliant purple. In each case the color on the screen is the complement of that which is cut out.

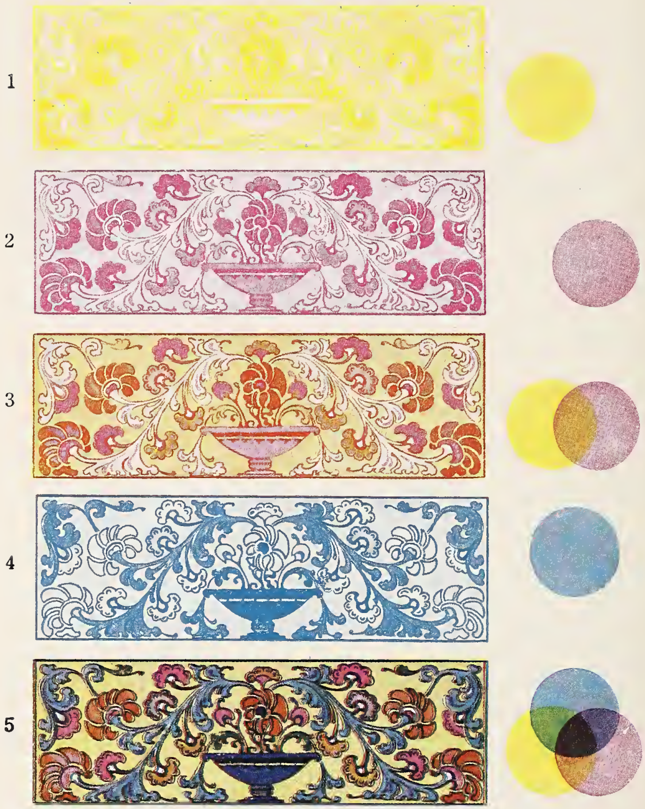
Retinal fatigue. Fix the gaze intently for not less than 20 or 30 sec on a point at the center of a block of any brilliant color — for example, red. Then look off at a dot on a white wall or a piece of white paper, and hold the gaze fixed there for a few seconds. The brilliantly colored block will appear on the white wall, but its color will be the *complement* of that first looked at.

The explanation of this phenomenon, which comes from so-called *retinal fatigue*, is found in the fact that although the white surface is sending waves of all colors to the eye, the nerves which responded to the color first looked at have become fatigued, and hence fail to respond to this color when it comes from the white surface. Therefore the sensation produced is that caused by white light minus this color, that is, the complement of the original color. A study of the spectral colors by this method shows that the following colors are complementary:

Red	Orange	Yellow	Violet	Green
Bluish green	Greenish blue	Blue	Greenish yellow	Crimson

Color of pigments. When yellow light is added to the proper shade of blue, white light is produced, since these colors are complementary. But if a yellow pigment is added to a blue one, the color of the mixture will be green. This is because the yellow pigment removes by absorption the blue and violet from white light falling on it, and the blue pigment removes the red and yellow, so that only green light is left.

When pigments are mixed, therefore, each one *subtracts* certain colors from white light, and the color of the mixture is that color which escapes absorption by the different ingredients. Adding *pigments* and adding *colors* (see page 544) are therefore wholly dissimilar processes and produce widely different results.



Three-Color Printing

1, yellow impression (negative made through a blue-violet filter); 2, crimson impression (negative made through a green filter); 3, crimson on yellow; 4, blue impression (negative made through a red filter); 5, yellow, crimson, and blue combined (the final product). The circles at the right show the colors of ink used in making each impression. Notice the different colors in 5, which are made by combining yellow, crimson, and blue

Three-color printing. It is found that all colors can be produced by suitably mixing with the color disk (Fig. 504) three spectral colors, namely red, green, and blue-violet. These are therefore called the *three primary colors.* The so-called primary pigments are simply the complements of these three primary colors. They are, in order, peacock blue, crimson, and light yellow. The three primary colors when mixed yield white. The three primary pigments when mixed yield black, because together they subtract all the ingredients from white light. The process of three-color printing consists in mixing on a white background, that is, on white paper, the three primary *pigments* in the following way: Three different photographs of a given-colored object are taken, each through a *filter* of gelatin stained the color of one of the primary colors. From these photographs half-tone *blocks* are made in the usual way. The colored picture is then made by carefully superposing prints from these blocks, using with each an ink whose color is the complement of that of the filter through which the original negative was taken. The plate on the opposite page illustrates the process fully. It will be interesting to examine differently colored portions with a lens of moderate magnifying power.

Colors of thin films. The study of complementary colors has furnished us with the key to the explanation of the fact, observed on page 542, that the upper edge of each colored band produced by the water wedge is reddish, whereas the lower edge is bluish. On the upper edge the shorter blue waves are destroyed by interference and a complementary red color is left; but on the lower edge of each fringe, where the film is thicker, the longer red waves interfere, leaving a complementary blue. In fact, each wave length of the incident light produces a set of fringes, and it is the superposition of these different sets which gives the colored fringes. Where the film is too thick the overlapping is so complete that the eye is unable to detect any trace of color in the reflected light.

In films which are of uniform thickness, instead of wedge-shaped, the color is also uniform so long as the observer does

not change the angle at which the film is viewed. With any change in this angle the thickness of film through which the light must pass in coming to the observer changes also, and hence the color changes. This explains the beautiful play of iridescent colors seen in soap bubbles, thin oil films, mother-of-pearl, etc.

Chromatic aberration. Up to this point we have assumed that all the waves which fall on a lens from a given source are brought to one and the same focus. But since blue rays are bent more than red ones in passing through a prism, it is clear that in passing through a lens the blue light must be brought to a focus at some point v (Fig. 506) nearer the lens than r, where the red light is focused, and that the foci for intermediate colors must fall in intermediate positions. It is for this reason that an image formed by a simple lens is always fringed with color.

Hold a card at the focus of a lens placed in a beam of sunlight (Fig. 506). If the card is slightly nearer the lens than the focus, the spot of light will be surrounded by a red fringe, for the red rays, being least refracted, are on the outside. If the card is moved out beyond the focus, the red fringe will be found to be replaced by a blue one; for after crossing at the focus those rays which are bent most will be found outside.

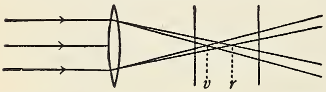


FIG. 506. Chromatic aberration of lens

This dispersion of light produced by a lens is called *chromatic aberration.*

Achromatic lenses. The color effect caused by the chromatic aberration of a simple lens greatly impairs its usefulness. Fortunately, however, it has been found possible to eliminate this effect almost completely by combining into one lens a convex lens of crown glass and a concave lens of flint glass (Fig. 507). The first lens produces both bending and dispersion, whereas the second almost completely overcomes the

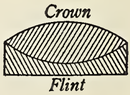


FIG. 507. An achromatic lens

dispersion without entirely overcoming the bending. Such lenses are called *achromatic lenses*. The first one to be described and patented was made by John Dollond in London in 1758. They are used in the construction of all good telescopes and microscopes.

Summary. **Pitch in sound and color in light depend upon wave frequency.**

Dispersion is due to unequal refraction of waves of different length when they pass obliquely into or out of a medium.

The color of a body depends on (1) the wave lengths of the light it receives and (2) the wave lengths of the light it is capable of reflecting or transmitting.

QUESTIONS AND PROBLEMS

A

1. What is the physical difference between red light and blue light?

2. Draw a figure to show how a spectrum is formed by a prism, and indicate the relative positions of the red, the yellow, the green, and the blue in this spectrum.

3. What determines the color of (*a*) an opaque body? (*b*) a transparent body?

4. (*a*) What is "white"? (*b*) What is "black"? (*c*) Why is coal black?

5. What is the appearance of a bunch of green grass when seen by pure red light? Explain.

6. Why do white bodies look blue when seen through a blue glass?

7. What color would a yellow object appear to have if looked at through a blue glass? (Assume that the yellow is a pure color.)

8. Why does dark blue appear black by candlelight?

9. If black objects absorb all the light that comes to them, how is it we can see them?

10. Do white-hot objects give off red light?

B

1. Does blue light travel more slowly or faster in glass than red light? How do you know?

2. A gas flame is distinctly yellow as compared with sunlight. What wave lengths must be comparatively weak in its spectrum?

3. Explain why a block of ice is transparent, whereas snow is opaque and white.

4. What will be the apparent color of a red body when it is in a room to which only green light is admitted? Why?

5. Why does any object seen through a piece of red glass appear to be either red or black?

6. Certain blues and greens cannot be distinguished from each other by candlelight. Explain.

7. Is the index of refraction of glass the same for red light as for green light? Give a reason for your answer.

8. If the velocity of light is 186,000 mi/sec, what is the velocity of yellow light through a diamond, a substance whose index of refraction for yellow light is 2.47?

9. Explain the ghastly appearance of the face of one who stands under the light of a Cooper-Hewitt mercury-vapor arc lamp.

10. (*a*) If you mixed paints of all the primary colors together, what would be the color of the resulting paint? (*b*) If you mixed light of these colors, what would be the color of the resulting light? Explain.

Spectra

The rainbow. There is formed in nature a very beautiful spectrum with which everyone is familiar, the *rainbow.*

Fill a spherical bulb F (Fig. 508) $1\frac{1}{2}$ or 2 in. in diameter with water and hold it in the path of a beam of sunlight which enters the room through a hole in a piece of cardboard AB. A miniature rainbow will be formed on the screen around the opening, the violet edge of the bow being toward the center of the circle and the red outside. A beam of light which enters the flask at C is there both refracted and dispersed; at D it is totally reflected; and at E it is again refracted and

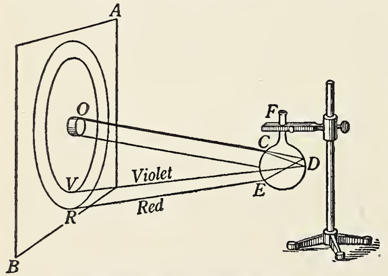


FIG. 508. Artificial rainbow

dispersed on passing out into the air. Since in both the refractions the violet is bent more than the red, it is obvious that it must return nearer to the direction of the incident beam than the red rays. If the flask were a perfect sphere, the angle included between the incident ray *OC* and the emergent red ray *ER* would be 42°, and the angle between the incident ray and the emergent violet ray *EV* would be 40°.

The actual rainbow seen in the heavens is caused by the refraction and reflection of light in the drops of water in the air, which act exactly as did the flask in the preceding experiment. If the observer is standing at *E* with his back to the sun, the light which comes from the drops so as to make an

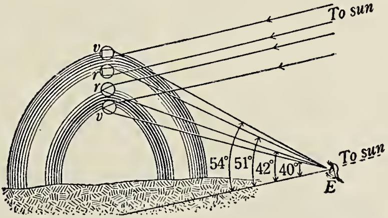


FIG. 509. Primary and secondary rainbows

angle of 42° (Fig. 509) with the line drawn from the observer to the sun must be red light; and the light which comes from drops which are at an angle of 40° from the eye must be violet light. In direct sunshine the prismatic color seen in a dew-drop changes to another color when the head is shifted sidewise. It is clear that those drops whose direction from the eye makes any particular angle with the line drawn from the eye to the sun must lie on a circle whose center is on that line. Hence we see a circular arc of light which is violet on the inner edge and red on the outer edge. A second bow having the red on the inside and the violet on the outside is often seen outside the one just described, and concentric with it. This bow arises from rays which have undergone two internal reflections and two refractions, in the manner shown in Fig. 509.

Continuous spectra. Place behind a slit *s* (Fig. 510) a Bunsen burner arranged to produce a white flame. View the slit through a prism *P*. The spectrum will be a continuous band of color. If the air is admitted at the base of the burner and a clean platinum wire held in the flame directly in front of the slit, the white-hot platinum will also give a continuous spectrum.*

All incandescent solids and liquids are found to give spectra of this type, which contain all the wave lengths from the extreme red to the extreme violet. The continuous spectrum of a luminous gas flame comes from the incandescence of solid particles of carbon suspended in the flame. The presence of these solid particles is proved by the fact that soot is deposited on bodies held in a white flame.

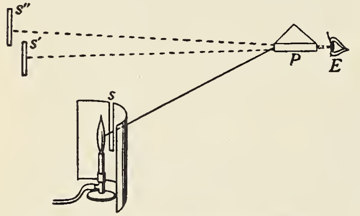
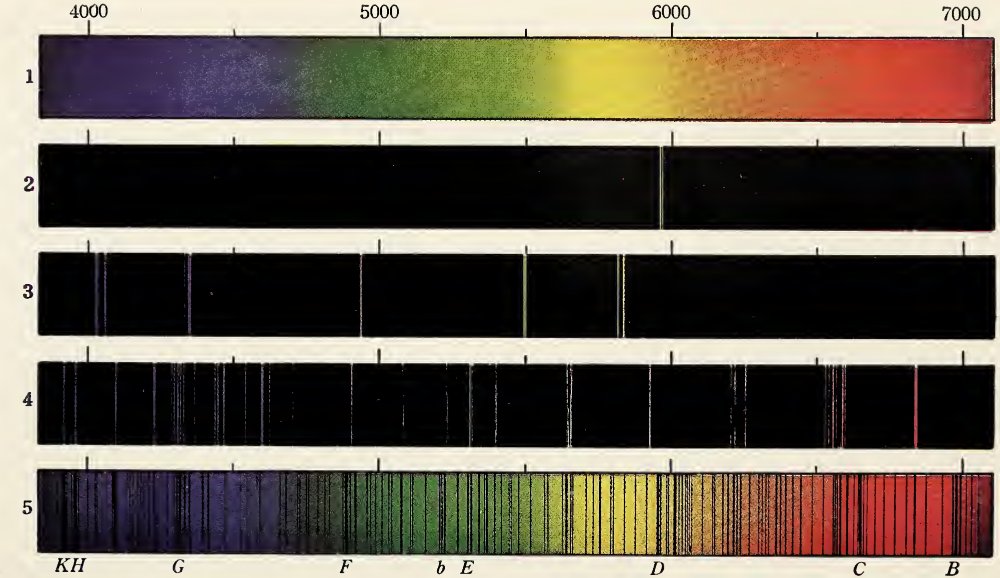


FIG. 510. Arrangement for viewing spectra

Bright-line spectra. Dip a bit of asbestos or a platinum wire into a solution of common salt (sodium chloride) and hold it in the flame, care being taken that the wire itself is held so low that the spectrum due to it cannot be seen. The continuous spectrum of the preceding paragraph will be replaced by a clearly defined yellow image of the slit, which occupies the position of the yellow portion of the spectrum. This shows that the light from the sodium flame is not a compound of a number of wave lengths, but is rather of just the wave length which corresponds to this particular shade of yellow. The light is now coming from the incandescent sodium vapor and not from an incandescent solid as in the preceding experiments.

Dip another platinum wire in a solution of lithium chloride and hold it in the flame. Two distinct images of the slit, s' and s'' (Fig. 510), will be seen, one in red and one in yellow. Introduce calcium chloride into the flame. One distinct image of the slit will be seen in the green and another in the red. Strontium chloride will give a blue and a red image; and so on. (The yellow sodium

* By far the most satisfactory way of performing these experiments with spectra is to provide the class with cheap plate-glass prisms, like those used in Experiment 63 of *Exercises in Laboratory Physics*, by Millikan, Gale, and Davis, rather than to attempt to project line spectra.



Different Types of Spectra

1, continuous spectrum from an incandescent solid; 2, bright-line spectrum of sodium; 3, bright-line spectrum of mercury; 4, bright-line spectrum of calcium; 5, absorption spectrum of the sun, showing Fraunhofer lines

image will probably be present in each case, because sodium is present as an impurity in nearly all salts.)

These narrow images of the slit in the different colors are called the characteristic *spectral lines* of the substances. The experiments show that incandescent vapors and gases give rise to *bright-line spectra,* and not continuous spectra like those produced by incandescent solids and liquids. (See on opposite page.) The method of analyzing compound substances through a study of the lines in the spectra of their vapors is called *spectrum analysis.* It was first used by Bunsen in 1859.

The solar spectrum. Let a beam of sunlight pass first through a narrow slit S (Fig. 511) not more than $\frac{1}{5}$ mm in width, then through a prism P, and finally let it fall on a screen S', as shown in Fig. 511. Change the position of the prism until a beam of white light is reflected from one of its faces to that portion of the screen which was previously occupied by the central portion of the spectrum. Then place a lens L between the prism and the slit, and move it back and forth until a perfectly sharp white image of the slit is formed on the screen. This adjustment is made in order to get the slit S and the screen S' in the positions of conjugate foci of the lens. Now turn the prism to its original position. The spectrum on the screen will then consist of a series of colored images of the slit arranged side by side. This is called a pure spectrum, to distinguish it from the spectrum shown in Fig. 503, in which no lens was used to bring the rays of each particular color to a particular point, and in which there was therefore much overlapping of the different colors. An arrangement of this kind is called a spectroscope. If the slit and screen are exactly at conjugate foci of the lens, and if the slit is sufficiently narrow, the spectrum will be seen to be crossed vertically by certain dark lines.

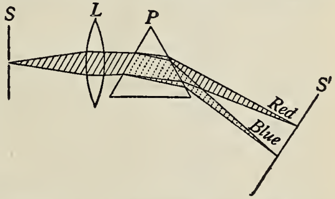


FIG. 511. Arrangement for obtaining a pure spectrum

These lines were first observed by the Englishman Wollaston in 1802, and were first studied carefully by the German Fraunhofer in 1814, who counted and mapped out as many as seven hundred of them. They are called, after him, the

Fraunhofer lines. Their existence in the solar spectrum shows that certain wave lengths are absent from sunlight, or, if not entirely absent, are at least much weaker than their neighbors. When the experiment is performed as described above, it will usually not be possible to count more than five or six distinct lines. Kirchhoff explained these lines.

Explanation of the Fraunhofer lines. Project the solar spectrum as in the experiment of Fig. 511. Lay a few small bits of metallic sodium upon a loose wad of asbestos which has been saturated with alcohol. Hold the asbestos so prepared to the left of the slit, or between the slit and the lens, and there ignite it. A black band will at once appear in the yellow portion of the spectrum, in the place where the color is exactly that of the sodium flame itself; or, if the focus was sufficiently sharp to permit a dark line to be seen in the yellow before the sodium was introduced, this line will grow very much blacker when the sodium is burned. Evidently, then, this dark line in the yellow part of the solar spectrum is in some way due to sodium vapor through which the sunlight has somewhere passed.

The experiment at once suggests the explanation of the Fraunhofer lines. The white light which is emitted by the hot nucleus of the sun, and which contained all wave lengths, has had certain wave lengths weakened by absorption as it passed through the vapors and gases surrounding the sun and the earth. For it is found that *every gas or vapor will absorb exactly those wave lengths which it is itself capable of emitting when incandescent.* This is for precisely the same reason that a tuning fork will respond to, that is, absorb, only vibrations which have the same period as those which it is itself able to emit. Since, then, the dark line in the yellow portion of the sun's spectrum is in exactly the same place as the bright yellow line produced by incandescent sodium vapor, or the dark line which is produced whenever white light shines through sodium vapor, we infer that sodium vapor must be contained in the sun's atmosphere.

Spectrum analysis. By comparing in this way the positions of the lines in the spectra of different elements with the positions of various dark lines in the sun's spectrum, many of

the elements which exist on the earth have been proved to exist also in the sun. For example, Kirchhoff showed that the four hundred and sixty bright lines of iron which were known to him were all exactly matched by dark lines in the solar spectrum. Fig. 512 shows a copy of a photograph of a portion of the solar spectrum in the middle, and the corresponding bright-line spectrum of iron each side of it. (This was taken from a portion of the blue only of the spectrum.) It will be seen that each bright line of iron coincides exactly with a dark line of the solar spectrum.

FIG. 512. Comparison of solar and iron spectra

Similarly the composition of many of the stars has been determined in this manner. The detailed and analytic study of the spectrum has been very important, too, in the verification of modern theories of light and of atomic structure.

[Doppler's principle applied to light waves. We have noted (see "The Doppler effect," p. 443) that the effect of the motion of a sounding body toward an observer is to shorten slightly the wave length of the note emitted, and the effect of motion away from an observer is to increase the wave length. Similarly, when a star is moving toward the earth, each particular wave length emitted will be slightly less than the wave length of the corresponding light from a source on the earth's surface. Hence in this star's spectrum all the lines will be displaced slightly toward the violet end of the spectrum. If a star is moving away from the earth, all its lines will be displaced toward the red end. From the direction and amount of displacement, therefore, we can calculate the velocity

with which a star is moving toward the solar system or receding from it. Observations of this sort have shown that some stars are moving through space toward the solar system with a velocity of 150 miles per second, while others are moving away from it with almost equal velocity. The whole solar system appears to be sweeping through space with a velocity of about 12 miles per second; but even at this rate it would be at least 70,000 years before the earth would come into the neighborhood of the nearest star, even if it were moving directly toward it.

Summary. **Continuous spectra are produced by light from incandescent solids and liquids.**

Bright-line spectra come from incandescent vapors or gases.

Absorption spectra are produced by light passing from an incandescent solid or liquid through an incandescent vapor or gas.

QUESTIONS AND PROBLEMS

A

1. In what part of the sky will a rainbow appear if it is formed in the early morning?

2. How does a continuous spectrum differ from that obtained when the source of light is a Bunsen burner in which sodium is being vaporized?

3. Why do we believe that there is sodium in the sun?

4. Draw a diagram of a slit, a prism, and a lens, so placed as to form a pure spectrum.

B

1. Why is a rainbow never seen during the middle part of the day?

2. Explain the cause of the formation of a continuous spectrum when light from an incandescent lamp is passed through a prism.

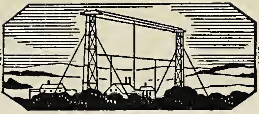
3. What sort of spectrum should moonlight give? (The moon has no atmosphere.)

4. If you were given a mixture of a number of salts, how would you proceed, with a Bunsen burner, a prism, and a slit, to determine whether or not there was any calcium in the mixture?

5. Can you see any reason why it is necessary to have the slit narrow and the slit and screen at conjugate foci of the lens in order to show the Fraunhofer lines in the experiment on page 553?

6. If a soap film is illuminated with red, green, and yellow strips of light, side by side, how will the distance between the yellow fringes compare (*a*) with that between the red fringes? (*b*) with that between the green fringes? (See table on page 542.)

7. Do two persons see the same rainbow at the same time? Explain.



UNIT SEVEN

Electronics and Invisible Radiations

WHAT we have studied thus far has told us almost nothing about what matter is made of. It is only in the last forty years that scientists have learned something about the internal structure of the atoms of matter, finding unbelievably tiny somethings called electrons. Partly by studying these elements of all matter they have found out a great deal about the many kinds of invisible rays that matter can be made to give off. Some, the so-called electromagnetic waves, such as X rays, gamma rays, and at least some of the cosmic rays, are like light waves, but of shorter wave length. Others, such as alpha and beta rays, are streams of particles given off when radioactive substances like radium and uranium go to pieces.

Physicists have studied these things largely from a curiosity about how the world is built, but their discoveries have almost immediately been applied to increasing the comfort and convenience of life. The speed with which application has followed theory shows the rapidity of modern technical advance. Within three decades of the discovery of the electron, electronic devices had transformed such old industries as those having to do with communication, and had created such new industries as broadcasting, sound motion pictures, and many less important ones.

Few physical devices have found in so short a time so many practical applications as has the electron-tube relay, or amplifier. The industries mentioned above, which would all be impossible or unimportant without

it, represent just a part of its useful applications. The biologist has discovered that there are very small electrical effects in our bodies every time we hear, see, feel, taste, think, contract our muscles, or indeed use any one of our senses. These electrical effects, previously too small to be dealt with in detail, can now be amplified by the electron tube to the point where they can be observed and accurately measured.

Investigating invisible radiations, physicists have found that the spectrum extends far out on both sides of the region of visible light — on the short-wave-length side from extreme violet through ultraviolet, X rays, and gamma rays up to the stupendously high frequencies of some of the cosmic rays, and on the other side down from the infrared through heat waves and short and long radio waves.

Most of the very short portions of the spectrum, discovered wholly in the search for knowledge, have been almost immediately applied in a practical way. An example is an instrument used every day by doctors and dentists in finding out what is wrong with their patients. This device, the X-ray tube, has made it possible to relieve the sufferings of millions of people. With radium it is proving to be an aid in the treatment of cancer.

Likewise ultraviolet radiation is used to make artificially vitamins which cure rickets, beriberi, and other diseases, giving us hope that these may at length be eliminated from the world.

Similarly on the long-wave-length end of the spectrum the development of diathermy (curing by "warming through") gives us a new weapon with which to roast bacteria out of the body. Finally, of course, the very long waves which bring us radio give us entertainment and news, save the lives of thousands in shipwreck and flood, and broaden our educational facilities.

We shall learn in the next few chapters something of how these new facts were discovered and some of the practical uses to which the knowledge has been put.

CHAPTER XXI

Properties of the Electron

Cathode Rays and X Rays

Discovery of the electron. Benjamin Franklin announced as early as 1749 that he believed in the existence of very minute and very easily moving electric particles, or atoms. He said, "The electrical matter consists of particles extremely subtle, since it can permeate common matter, even the densest metals, with such ease and freedom as not to receive any perceptible resistance." Franklin, along with many others, was trying to find out what an electric current *is*. Up to this point it has not been necessary to consider this problem. In Unit IV we were able to describe static and current electricity in terms of what electrical charges and currents *do*, without considering of what they are composed. Thus it is often possible in physics to set up laws describing how a thing like electricity or light *acts* without knowing of what it is made.

Indeed, all the laws contained in Unit IV were established before physicists agreed or needed to agree as to whether or not electricity is granular, that is, composed of particles. It was not until the very last years of the nineteenth century that the work of J. J. Thomson* and others convinced most scientists of the granular nature of an electrical charge and of an electric current. Some of the evidence leading to this conclusion is given in this chapter.

The electric spark in partial vacuums. Let *a* and *b* (Fig. 513) be the terminals of an induction coil or static machine; *e* and *f*, electrodes sealed into a glass tube 60 or 80 cm long; *g*, a rubber tube leading to an air pump by which the tube may be evacuated. Start

* He was knighted in 1908, becoming Sir Joseph Thomson.

the coil before the evacuation is begun. A spark will pass between *a* and *b*, since *ab* is a very much shorter path than *ef*. Then exhaust the tube rapidly. When the pressure has been reduced to a few centimeters of mercury, the discharge will be seen to choose the long path *ef* in preference to the short path *ab*, thus showing that *an electrical discharge takes place more readily through a partial vacuum than through air at ordinary pressures.*

When the spark first begins to pass between *e* and *f* it will look like a long ribbon of crimson light. As the pumping is continued, this ribbon will spread out until the crimson glow fills the whole tube. Ordinary neon tubes, as used in the red advertising signs, are tubes like the one above except that they contain neon gas at low pressures instead of air and are usually twisted into various shapes. Other gases than neon, and the use of colored glass, have given a wide variety of colors to the sign tubes.

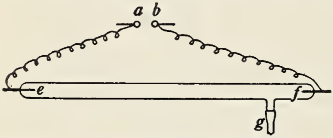


FIG. 513. Discharge in a partial vacuum

Cathode rays. When a tube like the one above is exhausted to a very high degree, say to a pressure of about .001 millimeter of mercury, the character of the discharge changes completely. The glow almost entirely disappears from the remaining, or residual, gas in the tube, and certain invisible radiations called *cathode rays* are found to be given off by the cathode (the terminal of the tube which is connected to the negative terminal of the coil or static machine). These rays manifest themselves, first, by the brilliant fluorescent effects which they produce in the glass walls of the tube, or in other substances within the tube upon which they fall; secondly, by powerful heating effects; and thirdly, by the sharp shadows which they cast.

Thus, if the negative electrode is concave, as in Fig. 514, and a piece of platinum foil is placed at the center of the sphere of which the cathode is a portion, the rays will come to a focus upon a small part of the foil and will heat it white-hot, thus showing that the rays, whatever they are, travel out in straight lines at right angles

to the surface of the cathode. This may also be shown nicely by an ordinary bulb of the shape shown in Fig. 518. If the electrode A is made the cathode and B the anode, a sharp shadow of the piece of platinum P in the middle of the tube will be cast on the wall opposite A, thus showing that the cathode rays, unlike the ordinary electric spark, do not pass between the terminals of the tube, but pass out in a straight line from the cathode surface.

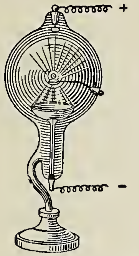


FIG. 514. Heating effect of cathode rays

Nature of the cathode rays. The nature of the cathode rays was a subject of much dispute between the years 1875, when they first began to be carefully studied, and 1898. Some thought them to be streams of negatively charged particles shot off with great speed from the surface of the cathode, and others thought they were waves in the ether — some sort of invisible light. The following experiment furnishes very convincing evidence on this point:

NP (Fig. 515) is an exhausted tube within which has been placed a screen *sf* coated with some substance like zinc sulfide which fluoresces brilliantly when the cathode rays fall upon it; *mn* is a mica strip containing a slit *s*. This mica strip stops all the cathode rays which strike it; but those which pass through the slit *s* travel the full length of the tube, and although they are themselves invisible, their path is completely traced out by the fluorescence which they excite upon *sf* as they graze along it. If a magnet M is held in the position shown, the cathode rays will be seen to be deflected, and in exactly the direction to be expected if they consisted of negatively charged particles. For we learned on page 334 that a moving charge constitutes an electric current, and on page 394 that an electric current tends to move in an electric field in the direction given by the motor rule. On the other hand, a magnetic field exerts no appreciable influence on the direction of a beam of light or on any other form of ether waves.

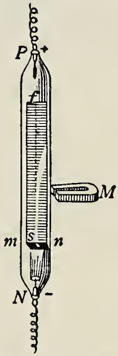


FIG. 515. Deflection of cathode rays by a magnet

When, in 1895, J. J. Thomson, of Cambridge, England, proved that the cathode rays were also deflected by electrical charges, as was to be expected if they consist of negatively charged particles, and when Perrin in Paris proved that they actually impart negative charges to bodies on which they fall, all opposition to the projected-particle theory was abandoned. The mass and speed of these particles are computed from their deflectability in magnetic and electrical fields.

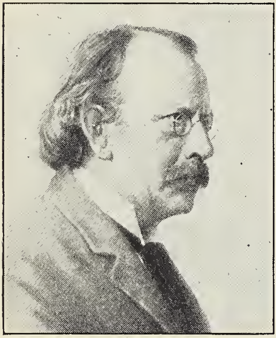


FIG. 516. Sir Joseph Thomson (1856–)

Most conspicuous figure in the development of the "physics of the electron"; born in Manchester, England; educated at Cambridge University; Cavendish professor of experimental physics in Cambridge from 1884 to 1912

Cathode rays are, then, today universally recognized as streams of electrons shot off from the surface of the cathode with speeds which may reach the stupendous value of 100,000 miles per second and more.

Electrons within atoms. Experiments with cathode rays have helped us to learn much about the minute structure of matter. First it is found by experiment that whatever metals are used for the electrodes and whatever residual gases are used in the tube, the cathode rays are always deflected in a given magnetic field by the same amount. This indicates that the same electrically charged particles, or *electrons*, of which the cathode rays are composed are present in all the ninety-two chemical elements.

Secondly we find that since cathode rays are always bent the same way in a magnetic field, they must be made up wholly of negative, never of positive, electrons. Since it is possible to pull off negative electrons from normally *neutral* atoms, we must infer that there are balancing positive charges left behind. Other kinds of evidence lead us to believe that the positive charge is all concentrated in a nucleus

around which the negative electrons are revolving in orbits of various types.

Electrons are the smallest and lightest objects known. It takes 1836 of them to have a mass equal to the mass of the lightest known atom, that of hydrogen. As early as 1890 the German physicist Lenard showed that a high-velocity stream of electrons, such as constitutes a cathode-ray beam, can pass right through a vacuum tube having a very thin wall without impairing the vacuum. Coolidge has extended these experiments.

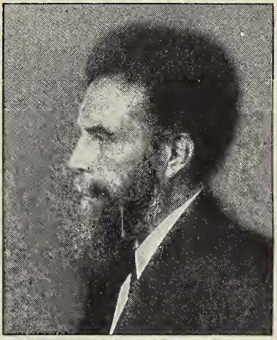


FIG. 517. Wilhelm Konrad Roentgen

Discoverer of X rays

X rays. It was in 1895 that Roentgen first discovered that wherever the cathode rays strike upon the walls of a tube, or upon any obstacles placed inside the tube, they give rise to another type of invisible radiation which is now known under the name of *X rays* or *Roentgen rays*. In the X-ray tube (Fig. 518) a thick piece of platinum or tungsten, called the anticathode, *P*, is placed in the center to serve as a target for the cathode rays, which, being emitted at right angles to the concave surface of the cathode *C*, come to a focus at a point on the surface of this plate. This is the point at which the X rays are generated and from which they radiate in all directions.

In order to convince oneself of the truth of this statement it is only necessary to observe an X-ray tube in action. It will be seen to be divided into two hemispheres by the plane which contains the platinum plate (Fig. 518). The hemisphere which is facing the source of the X rays will be aglow with a greenish fluorescent light, whereas the other hemisphere, being screened from the rays, is darker. By moving a fluoroscope (a zinc-sulfide screen) about the tube it will be made evident that the X rays come from *P*.

Nature of X rays. Although X rays are like cathode rays in that they produce fluorescence, they differ from cathode rays in several important respects. First, X rays penetrate many substances which are quite impervious to cathode rays; for example, they pass through the walls of the glass tube, whereas cathode rays ordinarily do not. Again, X rays are not deflected either by a magnet or by an electrostatic charge, nor do they carry electrical charges of any sort. Hence it is certain that they do not consist, like cathode rays, of streams of electrically charged particles.

It has been shown that X rays are extremely short waves similar to light waves but very much shorter, and of a variety of lengths. They are so short that the smoothest mirror we can manufacture is so rough in comparison with their length that it diffuses them. By taking advantage of the regular arrangement of the molecules in the faces of crystals (mica, for example) a kind of reflection known as interference reflection is obtained when the X rays strike at certain favorable angles. Many of the X rays from an ordinary X-ray tube are so short that it would require 250,000,000 of them to make an inch. This represents a rate of vibration of 3,000,000,000,000,000,000 per second.

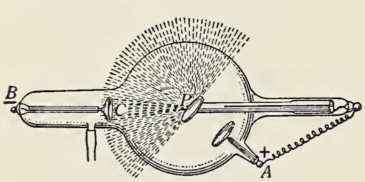
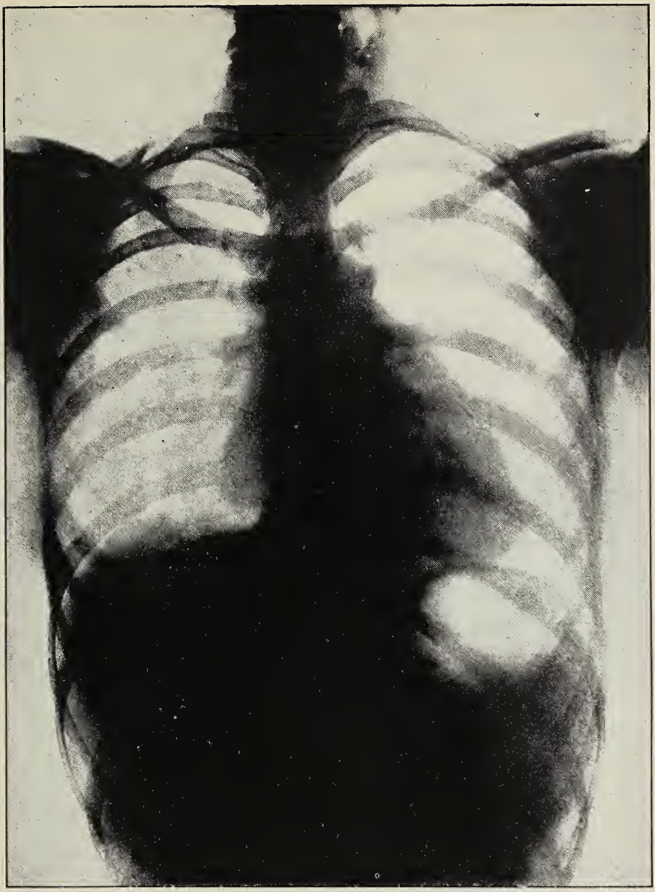


FIG. 518. An X-ray bulb

X rays render gases conducting. One of the notable properties which X rays possess in common with cathode rays is the property of causing any electrified body on which they fall to lose its charge slowly.

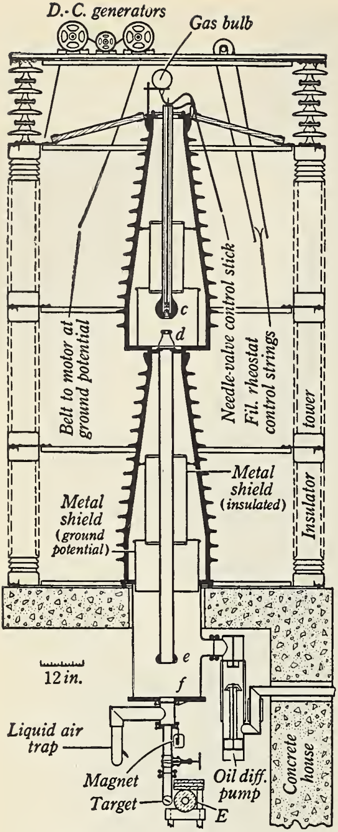
To demonstrate the existence of this property set any X-ray bulb in operation within 5 or 10 ft of a charged gold-leaf electroscope. The leaves at once begin to fall together.

The reason for this is that the X rays shake electrons loose from the atoms of the gas and thus fill it with positively and



X-Ray Picture of the Human Thorax

This figure is a heart-lung picture of the human thorax, with the apex of the heart showing clearly on the left of the spinal column and the base stretching across the column, part of it showing distinctly on the right side opposite the apex. X-ray photographs are a great help to physicians in treating tuberculosis



This is one form of the Lauritsen 1,000,000-volt tube. There has never been any difficulty in pushing up the voltage supplied by a transformer. The limitation has always inhered in the tube which must utilize and control the voltage. In 1929 C. C. Lauritsen and his associates first surmounted this difficulty, and by 1930 a 1,000,000-volt X-ray tube was in regular service. The penetrating power of its rays was found to be only slightly less than that of radium, and the intensity of its beam the equivalent of 100 grams of pure radium ($7,000,000 worth at the prices then existing). This tube has been used continuously since in modified form for transmutation experiments, and another modification, working up to 1,200,000 volts, is used for the treatment of deep-seated cancer.

As set up in the figure it is used for driving the positive nuclei of ordinary heavy hydrogen and helium against a target and thereby producing "transmutation of the elements." The source of these bombarding ions is the ionization of gas at about 0.001-millimeter pressure let in from the gas bulb shown at the top and ionized at the lower end of the metal tube *c* by a hot filament and a 1000-volt field supplied by direct-current generators at the top. The stream of positive ions emerges from the opening at the lower end of *c* and receives an acceleration of 500,000 volts between *c* and *d*. These ions move through the metal tube *de* without changing speed and receive their final 500,000 volts of acceleration between *e* and *f*, so that they are 1,000,000-volt ions when they strike the target, a 2-centimeter brass disk mounted on a shaft so that either side can be exposed to the ion beam. One side is covered with the material to be transmuted, and the other with some material which gives no effect, such as brass or aluminum. Such bombardment has been found in some cases to produce 16,000,000-electron-volt photons, which are analyzed by either a cloud chamber or a special electroscope placed at *E*

Lauritsen 1,000,000-Volt Tube

negatively charged particles, each negative particle being at the instant of separation an electron, and each positive particle an atom from which an electron has been detached. Any charged body in the gas therefore draws toward itself charges of sign opposite to its own, and thus becomes discharged.

X-ray pictures. The most striking property of X rays is their ability to pass through many substances which are wholly opaque to light — for example, cardboard, wood, leather, and flesh. Thus, if the hand is held close to a photographic plate and then exposed to X rays, a shadow picture of the denser portions of the hand, that is, the bones, is formed upon the plate. Opposite page 566 is shown an X-ray picture of the thorax of a living human being.

It is not too much to say that the discovery of X rays has revolutionized the work of both the dentist and the doctor. For locating abscesses and other imperfections of the teeth; for studying fractures of bones; for discovering disordered conditions of the internal organs; for locating foreign metallic substances within the body; for all kinds of diagnostic work, — for all these and for scores of other uses the X rays are one of the most indispensable tools of modern civilization. X rays of very high potential have also recently found extensive and important application in the treatment of cancer.

Summary. Cathode rays consist of streams of negative electrons emitted from the surface of the cathode.

The fact that all kinds of cathodes emit exactly the same sort of cathode rays indicates that electrons are constituents of all atoms.

It is believed that in a neutral atom the positive charge is all concentrated in the nucleus and that just enough negative electrons to balance this charge are revolving about this nucleus.

X rays are ether waves produced by the impact of cathode rays upon the anticathode.

X rays render gases conducting by knocking electrons out of their orbits, thus leaving behind positively charged atoms, or positive ions. The negative electrons attach themselves to neutral atoms or molecules and thus produce negative ions.

QUESTIONS AND PROBLEMS

1. Why do we think that cathode rays are negatively charged particles and not ether waves?

2. Why do we believe that X rays are ether waves and not charged particles?

3. Explain how X rays are used by the dentist and the doctor.

4. Try to find out from some outside source what precautions must be taken by X-ray operators to protect themselves from injury by the rays.

Radioactivity

Discovery of radioactivity. In 1896 Henri Becquerel, in Paris, performed the following experiment: He wrapped a photographic plate in a piece of perfectly opaque black paper, laid a coin on top of the paper, and suspended above the coin a small quantity of the mineral uranium. He then set the whole away in a dark room and let it stand for several days. When he developed the photographic plate, he found upon it a shadow picture of the coin similar to an X-ray picture. He concluded, therefore, that *uranium possesses the property of spontaneously emitting rays of some sort which have the power of penetrating opaque objects and of affecting photographic plates, just as X rays do.* He also found that these rays, which he called *uranium rays*, are like X rays in that they discharge electrically charged bodies on which they fall. He found also that the rays are emitted by all uranium compounds.

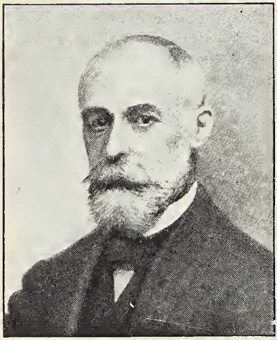


FIG. 519. Antoine Henri Becquerel, Paris
Discoverer of radioactivity

Radium. It was but a few months after Becquerel's discovery that Madame Curie, in Paris, began an investigation

of all the known elements, to find whether any of the rest of them possessed the remarkable property which had been found to be possessed by uranium. She found that one of the known elements, namely thorium, is capable, together with its compounds, of producing the same effect. After this dis-

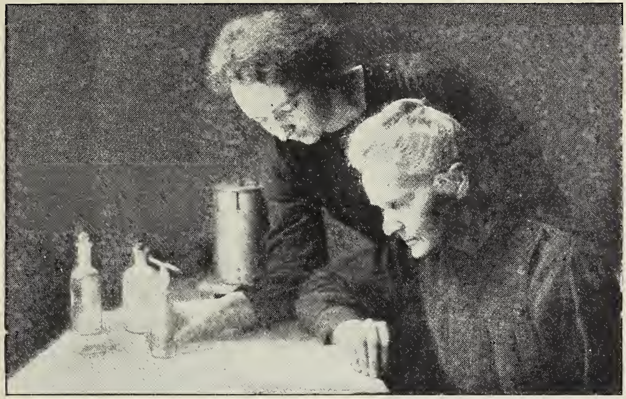


FIG. 520. Madame Curie and her daughter Irène, University of Paris

The first, discoverer of radium (1898); the second, with her husband, M. Joliot, discoverer of artificial radioactivity (1933)

covery the rays from all this class of substances began to be called *Becquerel rays*, and all substances which emitted such rays were called *radioactive* substances.

But in connection with this investigation Madame Curie noticed that pitchblende, the crude ore from which uranium is extracted, and which consists largely of uranium oxide, would discharge her electroscope about four times as fast as pure uranium. She inferred, therefore, that the radioactivity of pitchblende could not be due entirely to the uranium contained in it, and that pitchblende must therefore contain some hitherto unknown element which has the property of emitting Becquerel rays more powerfully than uranium or thorium. After a long and difficult search she succeeded in

separating from several tons of pitchblende a few hundredths of a gram of a new element which was capable of discharging an electroscope more than a million times as rapidly as either uranium or thorium. She named this new element *radium.*

Nature of Becquerel rays. That these rays which are spontaneously emitted by radioactive substances are not just X rays, in spite of their similarity in affecting a photographic plate, in causing fluorescence, and in discharging electrified bodies, is proved by the fact that they are found to be at least partially deflected by both magnetic and electrical fields, and further by the fact that they impart electrical charges to bodies upon which they fall. These facts constitute strong evidence that *radioactive substances eject from themselves electrically charged particles.*

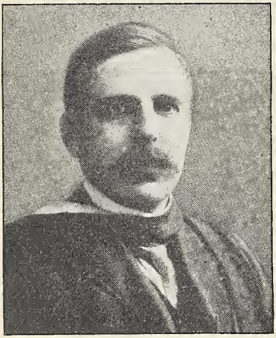


FIG. 521. Lord Rutherford, Cambridge University

Discoverer of radioactive transformations

But an experiment performed in 1899 by Rutherford, then of McGill University, Montreal, showed that Becquerel rays are complex, consisting of three different types of radiation, which he named the *alpha*, *beta*, and *gamma* rays. The beta rays are found to be identical in all respects with cathode rays; that is, *they are streams of electrons* projected with velocities varying from 60,000 to 180,000 miles per second. The alpha rays are distinguished from these by their very much smaller penetrating power, by their very much greater power of rendering gases conducting, by their very much smaller deflectability in magnetic and electrical fields, and by the fact that *the direction of the deflection is opposite to that of the beta rays.* (See Fig. 522.) From this last fact, discovered by Rutherford in 1903, the conclusion is drawn that the alpha rays consist of *positively* charged particles; and from the amount of their deflectability

their mass has been calculated to be about four times that of the hydrogen atom, — that is, about 7400 times the mass of the electron, — and their velocity to be about 20,000 miles per second. Rutherford and Boltwood have collected the alpha particles in sufficient amount to identify them definitely as *positively charged atoms of helium.*

The difference in mass between the alpha and beta particles explains in part why the latter, being light, are roughly a hundred times more penetrating then the former, and why the former, being heavy, are so much more efficient than the latter in knocking electrons out of the molecules of a gas and rendering it conducting. A sheet of aluminum foil .005 centimeter thick cuts off the alpha rays completely but offers practically no obstruction to the passage of the beta and gamma rays.

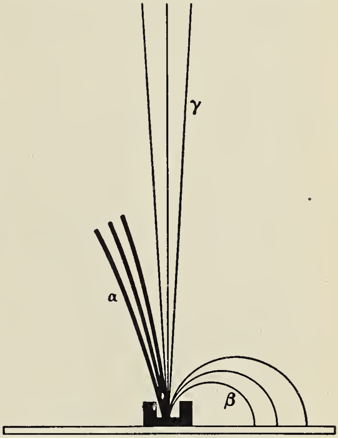


FIG. 522. The behavior of alpha, beta, and gamma rays in a magnetic field

The gamma rays are, in their turn, roughly a hundred times more penetrating than even the beta rays, and are not at all deflected by magnetic or electrical fields (Fig. 522). They are regular waves in the ether, like X rays, only shorter.

[**Crookes's spinthariscope.** In 1903 Sir William Crookes devised a little instrument, called the spinthariscope, which furnishes very direct and striking evidence that particles are being continuously shot off from radium with enormous velocities. In the spinthariscope a tiny speck of radium salt *R* (Fig. 523) is placed about a millimeter above a zinc-sulfide screen *S*, and the latter is then viewed through a lens *L*, which

gives from ten to twenty diameters magnification. The continuous soft glow of the screen, which is all one sees with the naked eye, is resolved by the lens into hundreds of tiny flashes of light (scintillations). The appearance is as though the screen were being fiercely bombarded by an incessant rain of projectiles, each impact being marked by a flash of light, just as sparks fly from a flint when struck with steel. The experiment is a very beautiful one, and it furnishes very direct and convincing evidence that radium is continuously projecting particles from itself at stupendous speeds. The flashes are due to the impacts of the *alpha*, not the *beta*, particles against the screen.

[A mixture composed of a radioactive compound and zinc sulfide glows constantly and is used for the dials of airplane instruments, compasses, and watches, as well as on gun sights, making them visible for night use.

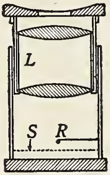


FIG. 523. Crookes's spinthariscope

Disintegration of radioactive substances. Whatever is the cause of this ceaseless emission of particles exhibited by all the radioactive substances, it is certainly not due to any ordinary chemical reactions; for Madame Curie showed, when she discovered the activity of thorium, that the activity of all the radioactive substances is simply proportional to the amount of the active element present, and has nothing whatever to do with the nature of the chemical compound in which the element is found. Furthermore, radioactivity has been found to be independent of all *physical* as well as chemical conditions. The lowest temperature as well as the highest does not appear to affect it in the least. Radioactivity, therefore, is as unalterable a property of the atoms of radioactive substances as is mass itself. It is now known that the atoms of radioactive substances are disintegrating (breaking up) into simpler atoms. Uranium and thorium have the heaviest atoms of all the elements. For some unknown reason they seem not infrequently to

become unstable and project off a part of their mass. This projected mass is the alpha particle. What is left of the atom after the explosion is a new substance with chemical properties different from those of the original atom. This new atom is, in general, also unstable and breaks down into something else. This process is repeated over and over again until some stable form of atom is reached. Somewhere in the course of this atomic catastrophe some electrons leave the mass; these are the beta rays.

According to this point of view, which is now generally accepted, radium is simply one of the stages in the disintegration of the uranium atom. The atomic weight of uranium is 238; that of radium, about 226; that of helium, 4.00. Radium would then be uranium after the latter has lost 3 helium atoms. Uranium disintegrates very slowly. The time required for half of a given mass of uranium to disintegrate, the so-called *half-life*, is 4,700,000,000 years. There are four definite chemical products between uranium and radium, with half-lives successively of 24.6 days, 1.15 minutes, 2,000,000 years, and 70,000 years. The half-life of radium is 1690 years. Nine additional radioactive products have been identified in the succession following radium. The final product is lead, which is apparently stable. The half-life of the intervening substances ranges from about .000001 second for RaC′ (radium C prime) to 16 years for RaD (radium D). Most of the others have a half-life of a few minutes or a few days.

Energy given off by radioactive substances. In 1903 the two Frenchmen Curie and Labord made a discovery that was significant. It was that radium is continuously evolving heat at the rate of about 100 calories per gram per hour. More recent measurements have given 118 calories. This result was to have been expected from the fact that the particles which are continuously flying off from the disintegrating radium atoms are constantly bombarding the interior of the whole mass, thus raising its temperature. This measurement of the exact amount of heat evolved per hour enables us to estimate how much heat energy is produced in the disintegra-

tion of 1 gram of radium. It is about 2,000,000,000 calories — more than 200,000 times as much as is evolved in the combustion of 1 gram of the best grade of anthracite.

This might have large significance for the future of the world's power were it not for the fact that there are only three important radioactive families, namely uranium, thorium, and actinium and their disintegration products. But these are so rare that the total energy to be expected from them is altogether insignificant in comparison with that from coal. When the world's supply of coal and oil is gone, man will probably have no large source of energy except the radiant heat coming directly to him from the sun or indirectly through the growth of wood and other organic materials.

Summary. **Radioactive substances spontaneously emit three sorts of rays:**

1. *Alpha rays.* These are positively charged atoms of helium.

2. *Beta rays.* These are negatively charged electrons.

3. *Gamma rays.* These are like X rays but of much shorter wave length.

The disintegration of 1 gram of radium produces 300,000 times as much heat as is evolved in the combustion of 1 gram of coal.

QUESTIONS AND PROBLEMS

1. Explain the scintillations seen in a spinthariscope.

2. (*a*) How could you test a substance to find out whether or not it is radioactive? (*b*) How could you measure its activity?

3. What is the relation between uranium and radium?

4. Why is it unlikely that we shall ever use radioactivity as a large source of power?

Thermionic Effects

Boiling electrons out of metals. In X-ray tubes of the type shown in Fig. 518 large numbers of positively charged particles, or ions, are driven with great force against the cathode C by the intense electrical field in the tube. The negative electrons actually come from the atoms of the cathode be-

cause of this heavy bombardment. Such a tube will not work when the vacuum is very high, because there is then no residual gas to supply the bombarding positive ions.

But Edison discovered as early as 1883 that in a device like that shown in Fig. 524 a negative current can be drawn, even in a very high vacuum, from the hot filament to the plate. O. W. Richardson, of Cambridge, England, about 1900, studied carefully these negative currents emitted by incandescent wires and found that they consist merely of negative electrons that are "boiled out" of the hot filaments. (This is called the *thermionic effect.*) He found, too, that the number of these electrons emitted from the filament increases very rapidly with temperature, so that a wire like tungsten, which can be raised to a very high temperature without melting, is an efficient electron-emitter. In the most common form of X-ray tube,

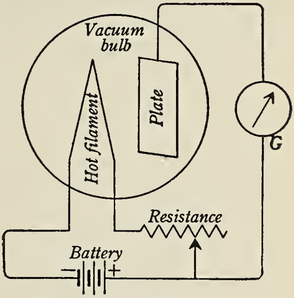


FIG. 524. Edison effect

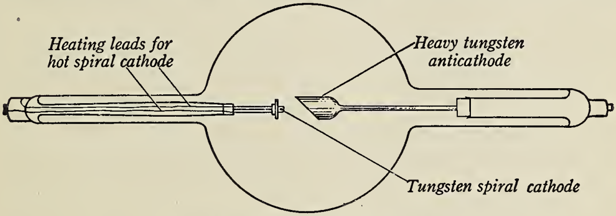


FIG. 525. Coolidge X-ray tube

therefore, the vacuum is made just as high as possible, and the source of the electrons for the cathode rays is a hot tungsten spiral, as shown in Fig. 525. Such a tube is generally called a Coolidge tube from its inventor, W. D. Coolidge, of Schenectady.

Electron valves. In 1905 the thermionic effect was utilized by J. A. Fleming in England for the construction of the so-called Fleming valve, which is used to change an alternating to a direct, pulsating current. Thus in the device shown in Fig. 526 a stream of electrons will flow to the plate when the *B* battery is connected as shown, but no current will flow when the *B* battery is reversed, since the electrons coming out of the hot filament are now driven back into it by the field. The reversal of the *B* battery corresponds, in the Fleming valve, to the reversals of the alternating current.

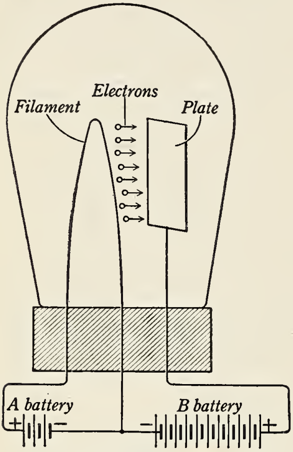


FIG. 526. Fleming valve

In the early days of radio, Fleming valves were suggested and used for the detection of dot-dash radio signals. The current set up in antennae, or aerials, by radio waves is an alternating current. If the *B* battery (Fig. 526) is replaced by any source of alternating current, a negative current will flow to the plate during the half-cycle in which the filament is negative, and no current during the half-cycle in which the filament is positive. The tube thus becomes an electron valve. Radio waves which reach the receiving aerial set up in it alternating currents of very high frequency, millions of cycles per second. When connected to a Fleming valve these currents can flow only in one direction, since the electrons flow only from the hot filament to the cold plate; hence they may be used to operate a direct-current instrument, such as a galvanometer, or to move the diaphragm of a telephone receiver. If the radio waves are sent out as dots and dashes, these signals will then be heard in the telephone receiver.

The De Forest "Audion." In 1907 De Forest inserted a metallic grid between the plate and the filament of the Fleming valve and thus transformed it into the "Audion," or "Triode," a *three-electrode tube* (Fig. 527). In its use the *B* battery is connected between plate and filament, whereas the terminals of "the line," or the antennae and ground, are attached to the filament and the grid. The fluctuating potentials thus applied between filament and grid permit varying numbers of electrons to pass from the filament through the openings in the grid to the plate. Variable currents thus flow in the plate circuit as long as the grid potential continues to vary. If the grid is made sufficiently negative (— 10 volts for the tube whose characteristic is shown in Fig. 528) no electrons can reach the plate. When the radio waves are added to the grid, that part of the waves which makes the grid less negative acts like a valve, or shutter, to permit some of the electrons to flow to the plate and operate the phones, whereas that part of the waves which makes the grid still more negative causes no change, since the plate, or phone, current is already zero. Thus, with a *C*-bias battery, the "Triode" rectifies, or "detects," the signals and may be used in place of a Fleming valve. The "Triode" has the additional advantage that only small potentials on the grid are needed to control the comparatively large currents of the *B* battery.

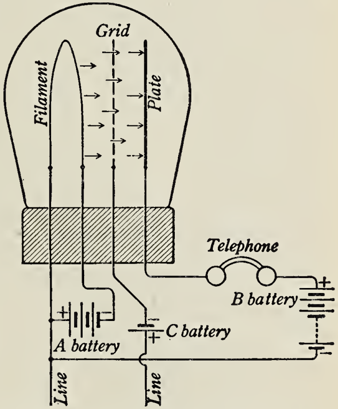


FIG. 527. The De Forest "Audion," or "Triode"

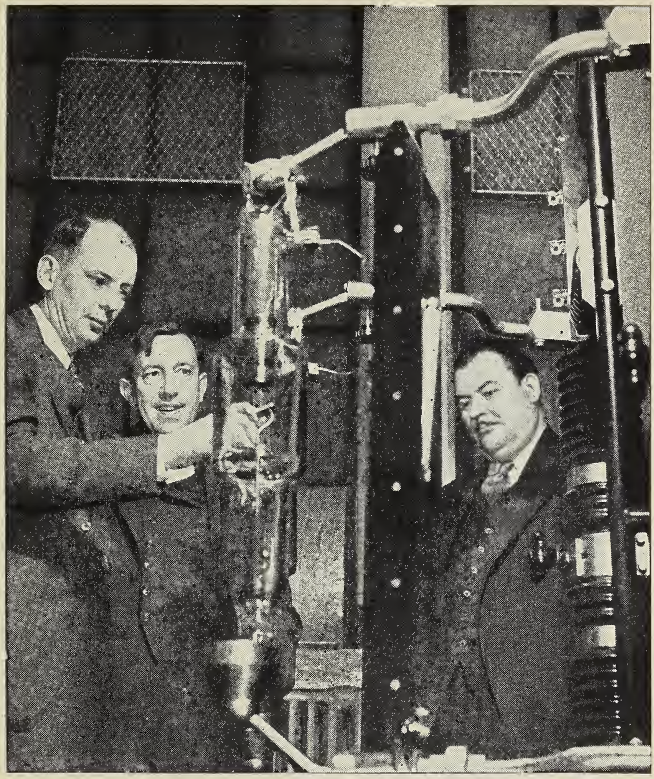
The development of the telephone relay, or amplifier. Up to about 1910 the properties of electron currents in tubes which

were exhausted to the highest attainable vacuums had been studied in great detail primarily by physicists in university laboratories. But by 1910 or 1911 there began to be developed in the United States an insistent commercial demand for long-distance telephony, in particular between New York and California. The engineers of the Bell Telephone Company recognized that the only way to achieve such telephony was to develop a telephone relay. Such a relay would have to take the highly complicated wave forms corresponding to the currents set up in a telephone line by the voice, and amplify them without distortion into very strong currents.

It appeared to the telephone engineers that the best way to solve this problem was to utilize in some way the inertialess electron streams that the physicists had been working on so diligently in their laboratories during the preceding decade. They solved it so well that by the summer of 1914 commercial telephone service was in operation between New York and San Francisco. This result was accomplished by relaying speech through as many as eight distortionless amplifiers and as many different circuits; there are now as many as forty. The telephone relay, or amplifier, used for this amplification was in fact the De Forest three-electrode "Audion" pumped down to a practically perfect vacuum, a modification necessary for distortionless amplification of speech. This amplifier has made possible not only long-distance telephony but the whole radio industry, the sound-motion-picture industry, and a multitude of other modern activities.

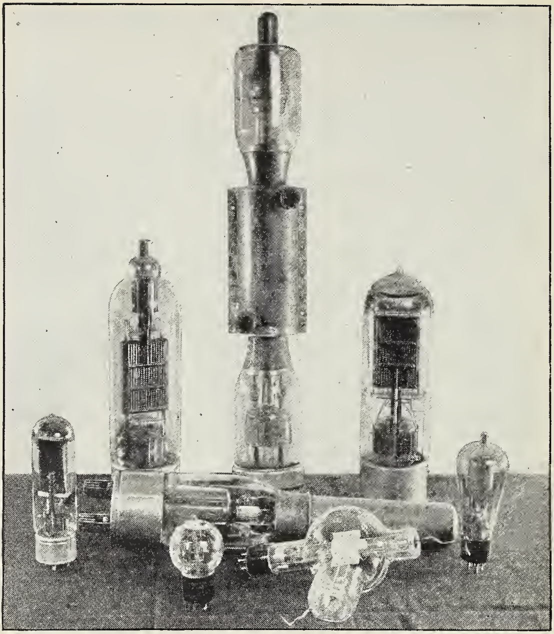
How the vacuum-tube amplifier works. To reproduce or amplify speech without distortion it is necessary that the strong currents coming from the plate circuit vary in just the same way as the weak currents to be amplified. This means that *changes in the plate current must be proportional to changes in the grid voltage*, or, in other words, these two quantities must bear a *linear* * relation to each other. The actual relation between grid potential and plate current determined by direct

* A linear relation exists when the graph of two quantities is a straight line.



X rays

X-rays depend upon electrons given off at enormous velocity by high-potential discharge from a heated tungsten filament. When these electrons strike a cold tungsten target the impact causes short electromagnetic waves to be produced. These are the Roentgen rays, or X rays. They have great penetrating power. The first use of these rays was in medical diagnosis, but more recently they have found wide application in industry for detecting defects in materials. Science has also found them useful in the study of atomic and crystal structure. The powerful X-ray tube shown in this illustration makes possible pictures through one inch of steel armor plate. (Courtesy of Westinghouse)



Set of Power Tubes up to 10,000 Watts Used in 1936 in World-Encircling Telephony

The rapid expansion of nation-wide and international telephone service has been hastened by the physicist in his development of the various vacuum tubes employed in the wire and radio circuits. Above are shown eight types of vacuum tubes used in the transpacific radio-telephone transmitting station of the Bell System, at Dixon, California. The largest tube, 30 inches high, which amplifies voices on their way from San Francisco to Tokyo, operates at a working temperature of 120° F. and is water-cooled. The water circulates at the rate of 2 gallons a minute and is constantly cooled by blowers in a manner similar to that in which the water is cooled in an automobile engine. *Rear row:* 250-watt radio-frequency stage tube; 10,000-watt double-ended water-cooled output-amplifier tube; 250-watt audio-frequency stage tube. *Center:* 10,000-watt rectifier tube used in 10,000-volt water-cooled six-phase rectifier. *Front row:* 50-watt speech-amplifier; 5-watt crystal oscillator; 75-watt harmonic generator tube; 10-watt crystal amplifier tube. (Courtesy of the Bell Telephone Laboratories)

laboratory measurements for a good amplifier tube is shown in Fig. 528. This figure shows that in this particular tube the grid must be 10 volts negative with respect to the filament in order to turn back all the electrons that are trying to get through the grid to the plate. And it shows that between grid potentials -5 and 0 volts the necessary linear relation for distortionless amplification exists. It shows also that if the weak speech currents coming in from the line cause variations in the potential on the grid between these limits, currents varying from about 2 to 8 milliamperes will flow through the plate circuit. If the grid is always kept negative, no electrons can reach it and hence no appreciable current need flow in the input circuit to produce the above-mentioned variations in the potential difference between filament and grid. This is the condition for large, distortionless amplification. A single tube of this sort may amplify the power a hundredfold. By repeating this operation through a series of such tubes it is possible to amplify telephone currents millions upon millions of times. Indeed, this is done continually in commercial practice.

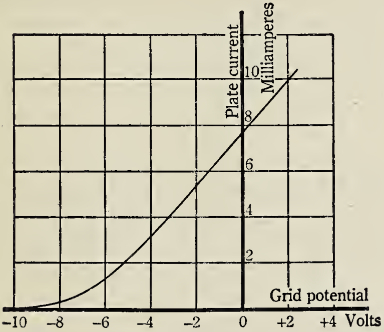


FIG. 528. Graph showing relation between plate current and grid potential

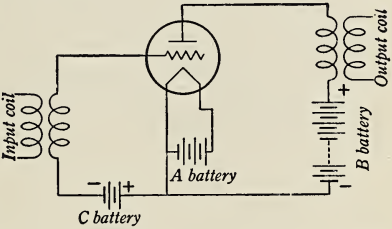


FIG. 529. Vacuum tube used as an amplifier

The usual connections for a "single stage" amplifier are shown in Fig. 529. The purpose of adding the *C* battery is to keep the grid always *negative.* The transformers marked "*Input coil*" and "*Output coil*" show the usual method of tying the input and output lines into the amplifier system.

Summary. Negative electrons evaporate from metals when they become sufficiently hot.

Electron valves reduce an alternating current to a unidirectional pulsating current.

A distortionless telephone relay requires a straight-line characteristic curve of grid potential and plate current.

The grid of a vacuum-tube relay, or amplifier, must at all times be negative with respect to the filament in order to prevent losses in the grid circuit and thus insure large distortionless amplification.

QUESTIONS AND PROBLEMS

1. What are the functions of the *A*, *B*, and *C* batteries used in amplifier tubes?

2. Describe the main steps in the process by which sound waves in New York are transformed into electric current and finally made to reappear as sound waves in Los Angeles.

3. What are the conditions necessary for the distortionless relaying of speech?

4. Why will no currents flow in a Fleming valve when the plate is negative with respect to the filament?

5. Why must the grid of an amplifier always be kept negative with respect to the filament?

CHAPTER XXII

Invisible Radiations

Radiation from a Hot Body

Invisible portions of the spectrum. When a spectrum is photographed, the photographic plate is found to be affected far out beyond the violet end of the visible spectrum. This indicates the presence of invisible rays of very short wave length. These so-called *ultraviolet rays* have been photographed down to a wave length of .0000004 centimeter (or 40 angstroms*), which is only one hundredth the wave length of the shortest violet waves. Indeed, the point at which the ultraviolet spectrum ends and the X-ray spectrum begins is now wholly arbitrary. The gap between the two regions of wave lengths has been completely bridged.

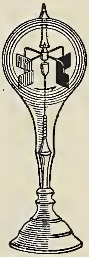


FIG. 530. The Crookes radiometer

The longest rays visible in the extreme red have a wave length of about .00008 centimeter (8000 angstroms); but delicate thermoscopes reveal a so-called *infrared* portion of the spectrum, the investigation of which was carried in 1912, by Rubens and Baeyer of Berlin, to wave lengths as long as .03 centimeter, 400 times as long as the longest visible rays.

The presence of these long heat rays may be detected by means of the radiometer (Fig. 530), an instrument perfected by E. F. Nichols at Dartmouth. In its common form it consists of a partially evacuated bulb, within which is a little aluminum wheel carrying four vanes blackened on one face and polished on the other. When the instrument is held in sunlight or before a lamp, the vanes rotate in

* An angstrom is $\frac{1}{100,000,000}$ centimeter; thus .00005896 centimeter is equal to 5896 angstroms, the wave length of yellow sodium light.

such a way that the blackened faces always move away from the source of radiation, because they absorb ether waves better than do the polished faces, and thus become hotter. The heated air in contact with these faces then exerts a greater pressure against them than does the cooler air in contact with the polished faces.

Place the radiometer just beyond the red end of the spectrum. It will indicate the presence here of heat rays of even greater energy than those in the visible spectrum. Further, place a red-hot iron ball and one of the detectors at conjugate foci of a large mirror (Fig. 531). The invisible heat rays will be reflected and focused just as are light rays. Next insert a flat bottle filled with water between the detector and any source of heat. It will be found that water, although transparent to light rays, absorbs nearly all the infrared rays. But if the water is replaced by carbon bisulfide, the infrared rays will be freely transmitted, even though the liquid has been made opaque to light waves by dissolving iodine in it.

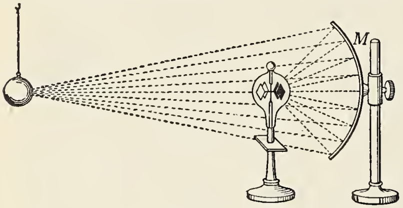


FIG. 531. Reflection of infrared rays

Radiation and temperature. All bodies, even such as are at ordinary temperatures, are continuously radiating energy in the form of ether waves. This is proved by the fact that even if a body is placed in the best vacuum obtainable, it continuously falls in temperature when surrounded by a colder body, for example liquid air. The ether waves emitted at ordinary temperatures are doubtless very long as compared with light waves. As the temperature is raised, more and more of these long waves are emitted, but shorter and shorter waves are continuously added. At about 525° C. the first visible waves, that is, those of a dull-red color, begin to appear. From this temperature on, because of the addition of shorter and shorter waves, the color changes continuously, — first to orange, then to yellow, and finally to white. In other words, all bodies get "red-hot" at about 525° C. and "white-hot" at from 800° C. to 1200° C.

Some idea of how rapidly the total radiation of ether waves increases with increase of temperature may be obtained from the fact that a hot platinum wire gives out thirty-six times as much light at 1400° C. as it does at 1000° C., although at the latter temperature it is already white-hot. The radiations from a hot body are sometimes classified as heat rays, light rays, and chemical, or actinic, rays. The classification is misleading, however, since all ether waves are heat waves in the sense that, when absorbed by matter, they produce heating effects, that is, molecular motions. *Radiant heat is, then, the radiated energy of ether waves of any and all wave lengths.*

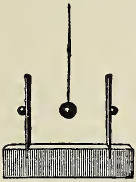


FIG. 532. Good reflectors are poor absorbers

Radiation and absorption. Although all substances begin to emit waves of a given wave length at approximately the same temperature, the total rate of emission of energy at a given temperature varies greatly with the nature of the radiating surface. In general, experiment shows that *surfaces which are good absorbers of ether radiations are also good radiators.* From this it follows that *surfaces which are good reflectors*, like the polished metals, *must be poor radiators.*

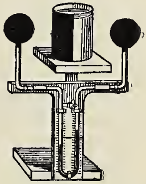


FIG. 533. Good absorbers are good radiators

Thus place two sheets of tin, 5 or 10 cm square, one brightly polished and the other covered on one side with lampblack, in vertical planes about 10 cm apart, the lampblacked side of one facing the polished side of the other. With a bit of wax stick a small ball to the outer face of each. Then hold a hot metal plate or ball (Fig. 532) midway between the two. The wax on the tin with the blackened face will melt and its ball will fall first, showing that the lampblack absorbs the heat rays faster than does the polished tin. Now connect two blackened glass bulbs, as in Fig. 533, through a U-tube containing colored water, and fill a well-polished tin can, one side of which has been blackened, with boiling water and place it between them. The motion of the water

in the U-tube will show that the blackened side of the can is radiating heat much more rapidly than the other, although the two are at the same temperature.

Make a black spot on a sheet of white paper with graphite, lamp-black, or charcoal, and then with a lens held in sunshine find what time is required to set fire to the paper when the light is concentrated on the black spot. Note the time required when the light is concentrated on the white part of the paper.

Summary. **Light waves comprise less than an octave of frequencies, an exceedingly small fraction of the total range of ether waves.**

Increase in temperature adds shorter and shorter waves and increases the intensity of all wave lengths.

Good absorbers are good radiators, and poor absorbers are poor radiators.

QUESTIONS AND PROBLEMS

1. (*a*) How are ultraviolet waves detected? (*b*) What apparatus is used to reveal infrared waves?

2. Which emits the more red rays, a white-hot iron or the same iron when it is red-hot?

3. Explain how the heat of the sun warms the earth.

4. Sunlight in coming to the eye travels a much longer air path at sunrise and sunset than it does at noon. Since the sun appears red or yellow at these times, what rays are absorbed most by the atmosphere?

5. When one is sitting in front of an open-grate fire, does one receive most heat by conduction, by convection, or by radiation?

6. Glass transmits all the visible waves, but does not transmit the long infrared rays. From this fact explain the principle of the hotbed.

7. Which will be cooler on a hot day, a white hat or a black one?

8. Will tea cool more quickly in a polished or in a tarnished metal vessel?

9. In your opinion which would be the more efficient, a polished, nickel-plated steam radiator or a rough, dark one? Explain.

10. The atmosphere is transparent to most of the sun's rays. Why are the upper regions of the atmosphere so much colder than the lower regions?

Electrical Radiations

Proof that the discharge of a Leyden jar is oscillatory. We found on page 467 that the sound waves sent out by a sounding tuning fork will set into vibration an adjacent fork, provided the latter has the same natural period as the former. The following is the complete electrical analogy of this experiment:

Connect the inner and outer coats of a Leyden jar *A* (Fig. 534) by a loop of wire *cdef*, the sliding crosspiece *de* being arranged so that the length of the loop may be altered at will. Also bring a strip of tin foil over the edge of this jar from the inner coat to within about 1 mm of the outer coat at *C*. Connect the two coats of an exactly similar jar *B* with the knobs *n* and *n′* by a second similar wire loop of fixed length. Place the two jars side by side with their loops parallel, and successively charge and discharge the jar *B* by connecting its coats with a static machine or an induction coil. At each discharge of jar *B* through the knobs *n* and *n′* a spark will appear in the other jar at *C*, provided the crosspiece *de* is so placed that the lengths of the two loops are equal. When *de* is slid along so as to make one loop considerably larger or smaller than the other, the spark at *C* will disappear.

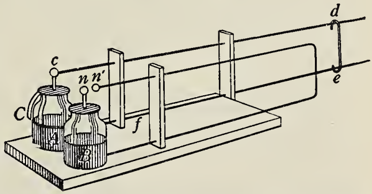


Fig. 534. Sympathetic electrical vibrations

The experiment therefore demonstrates that two electric circuits, like two tuning forks, can be *tuned* so as to respond to each other sympathetically, and that just as the tuning forks will cease to respond as soon as the period of one is slightly altered, so this *electrical resonance* disappears when the exact symmetry of the two circuits is destroyed. Since obviously this phenomenon of resonance can occur only between systems which have *natural periods* of vibration, the experiment proves that the discharge of a Leyden jar is a vibratory, that is, an oscillatory, phenomenon. As a matter

of fact, when such a spark is viewed in a rapidly revolving mirror it is actually found to consist of from ten to thirty flashes following one another at equal intervals. Fig. 535 is a photograph of such a spark.

FIG. 535. Oscillations of the electric spark

In spite of these oscillations the whole discharge may be made to take place in the incredibly short time of $\frac{1}{1,000,000}$ of a second. This fact, coupled with the extreme brightness of the spark, has made possible the surprising results of so-called *instantaneous electric-spark photography*. (See opposite pages 325 and 504.) The plate opposite page 504 shows the passage of a bullet through a soap bubble. The illuminating flash was so nearly instantaneous that the outlines are not blurred.

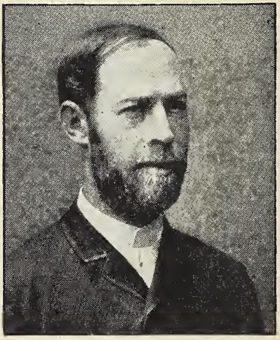


FIG. 536. Heinrich Rudolph Hertz (1857–1894)

German physicist, discoverer of the electromagnetic waves predicted by Maxwell. Wireless telegraphy is merely an application of this discovery

Electric waves. The experiment of the preceding section demonstrates not only that the discharge of a Leyden jar is oscillatory but also that these electrical oscillations set up in the surrounding medium disturbances or waves of some sort, which travel to a neighboring circuit and act upon it precisely as the air waves acted on the second tuning fork in the sound experiment. Whether these are waves in the air like sound waves, or disturbances in the ether like light waves, can be determined by measuring their velocity of propagation. The first determination of this velocity was made by Heinrich Hertz in 1888. He found it to be precisely the same as that of light, that is, 300,000 kilometers per second. *This result shows, therefore, that elec-*

trical oscillations set up waves in the ether. These waves are now known as hertzian waves.

The length of the waves emitted by the oscillatory spark of instantaneous photography is evidently very great, namely about 300,000,000/10,000,000, or 30 meters, since the velocity of light is 300,000,000 meters per second, and since there are 10,000,000 oscillations per second; for we have seen, on page 442, that wave length is equal to velocity divided by the number of oscillations per second. By diminishing the size of the jar and the length of the circuit the length of the waves may be greatly reduced. Waves such as these, however, are millions of times longer than any visible light waves. By causing the electrical discharges to take place between two balls only a fraction of a millimeter in diameter, instead of between the coats of a condenser, electric waves have been obtained as short as 0.1 millimeter, shorter than the longest measured heat waves.

Detection of electric waves. In the previous experiment, on page 585, we detected the presence of the electric waves by means of a small spark gap C in a circuit almost identical with that in which the oscillations were set up. The visible spark may be employed for the detection of waves many feet away from the source; but for detecting the feeble waves which come from a source hundreds or thousands of miles away we must use the sounds which are produced in extremely sensitive telephone receivers, as explained in the next section, or we must amplify and strengthen the waves by means of vacuum tubes in order to operate a loud-speaker.

The electromagnetic theory of light. Since electric currents are always accompanied by magnetic fields, electrical disturbances must always be accompanied by magnetic disturbances, and electrical radiations are actually electromagnetic radiations. The study of electromagnetic radiations, like those discussed in the preceding paragraphs, has shown not only that they have the speed of light but that they are reflected, refracted, and polarized; in fact, that they possess all the properties of light waves, the only apparent difference

being in their greater wave length. Hence *modern physics regards light as an electromagnetic phenomenon*; that is, light waves are thought to be generated by the displacements of the electrically charged parts of the atoms. It was as long ago as 1864 that the Scotchman Clerk-Maxwell at

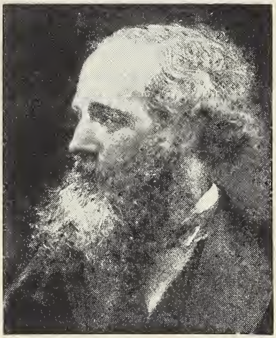


FIG. 537. James Clerk-Maxwell (1831–1879)

Professor of experimental physics in Cambridge University from 1871 to 1879; prominent in the development of the kinetic theory of gases and the mechanical theory of heat; author of the electromagnetic theory of light, proved experimentally by Hertz

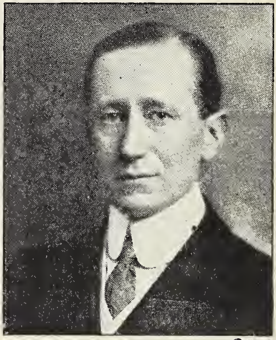


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FIG. 538. Guglielmo Marconi (1874–1937)

Inventor of commercial wireless telegraphy. In 1899, when he was twenty-five years old, he communicated between France and England by wireless. In 1901 at Poldhu, Cornwall, he received signals from St. John's, Newfoundland, a distance of 2100 miles

Cambridge, England, one of the world's most brilliant physicists and mathematicians, showed that it ought to be possible to create ether waves by means of electrical disturbances. But the experimental confirmation of his theory did not come until the time of Hertz's experiments (1888). Maxwell and Hertz together, therefore, share the honor of establishing the modern electromagnetic theory of light, perhaps the most important development of modern physics, since this theory has become the basis of nearly all modern theoretical work in electricity and optics.

Wireless telegraphy. Commercial wireless telegraphy was realized in 1896 by Marconi, eight years after the discovery of hertzian waves. The essential elements of a tuned *wave-train*, or "spark," system of wireless telegraphy are as follows:

[The key K at the transmitting station (Fig. 539 (a)) is depressed to allow a current from the alternator A to pass through the primary coil P of a transformer T_1, the frequency of the alternations which are commonly used being

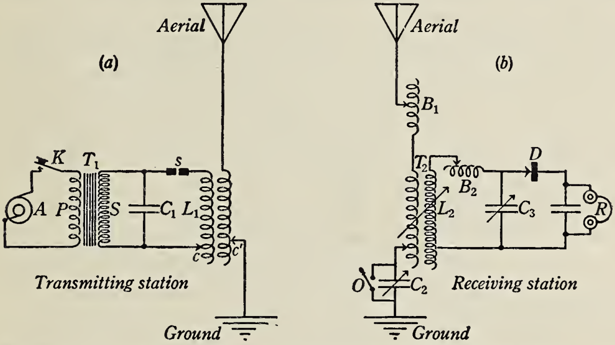


FIG. 539. Transmitting and receiving stations for wireless telegraphy. The straight parallel lines in T_1 denote an iron core. This is used at audio frequencies, but not at radio frequencies (see T_2)

about 500 cycles per second. The high-voltage current induced in the secondary S charges the condenser C_1 until its potential rises high enough to cause a spark discharge to take place across the gap s. This discharge of C_1 is oscillatory, and the oscillations thus produced in the condenser circuit containing C_1, s, and L_1 may, in a low-power, short-wave transmitting set, have a frequency as high as 1,000,000 per second.* An oscillation frequency much lower than this is generally used, and is subject to the control of the operator through the

* The frequency of oscillation f is given by $f = \frac{1}{2\pi} \times \frac{1}{\sqrt{LC}}$, which gives the frequency in cycles per second provided L is in henrys and C in farads.

sliding contact c, precisely as in the case illustrated in Fig. 534. The oscillations in the condenser circuit induce oscillations in the aerial-wire system, which is tuned to resonance with it through the sliding contact c'.

[As long as the key K is kept closed (assuming a 500-cycle alternator to be used), 1000 sparks per second occur at s, and therefore a regular series of 1000 wave trains (Fig. 540) pass off from the aerial every second and move away with the velocity of light. If the oscillations which produce a wave train have a frequency of say 500,000 per second, each wave in the wave train has a length of 300,000,000/500,000, or 600 meters; and if these wave trains are produced at the rate of 1000 per second, they follow one another at regular distances of 300,000 meters, that is, nearly 200 miles.

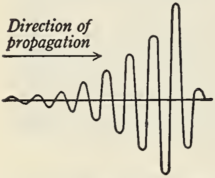


FIG. 540. One wave train from oscillatory discharge

[The waves sent out by the aerial system of the transmitting station induce like oscillations in the distant aerial system of the receiving station (Fig. 539 (b)) which is tuned to resonance with it. In case the receiving aerial must be tuned to respond to very long waves, the switch O is closed to cut out the condenser C_2, and the inductance, or loading coil, B_1 is used; whereas to tune to very short waves the switch O is opened and the variable condenser C_2 (see Fig. 270, p. 330) is brought into use, the loading coil not being utilized.* The oscillations in the aerial circuit of the receiving station induce exactly similar ones in the detector circuit to the right, which is tuned to resonance with the receiving aerial by means of L_2, B_2, and C_3. The so-called detector of these oscillations may be simply a crystal of galena D in series with

* In the diagram an arrow drawn diagonally across a condenser indicates that, for the sake of tuning, the condenser is made variable. Similarly an arrow across two circuits coupled inductively, like the primary and secondary of the oscillation transformer T_2, indicates that the amount of interaction of the two circuits can be varied, as, for example, by sliding one coil a longer or shorter distance inside the other.

the telephone receivers *R*. This crystal, like the tungar rectifier (p. 421), has the property of transmitting a current in one direction only.* Were it not for this property the telephone could not be used as a detector, because its diaphragm cannot vibrate with a frequency of the order of a million; and even if it could, it would produce sound waves far above the limit of hearing. Because of this rectifying property of the crystal the receiver diaphragm is drawn in only once while the oscillations produced by a given wave train last, this effect being produced by the rectified pulsating current which passes in one direction through the receivers and then ceases until the oscillations produced by the next spark arrive. Since one thousand of the intermittent wave trains strike upon the aerial each second, the operator at the receiving station hears *a continuous musical note of this pitch as long as the key K is depressed.* The working of the key, however, as in ordinary telegraphy, breaks the regular series of wave trains into *groups of wave trains,* so that the short and long notes heard in the receivers correspond to the dots and dashes of telegraphy. *The receiving station shown in Fig. 539 (b) may also be used for receiving wireless-telephone messages.*

[Although the spark, or wave-train, system of wireless telegraphy was once used almost exclusively, the "continuous wave" system has now almost entirely displaced it. This is because the continuous-wave signals tune more "sharply" — that is, cause less interference to the reception of other stations using slightly different frequencies — and because telephone messages as well as telegraph messages may be carried on the continuous waves.

[**Modulated continuous waves.** The vibrations constituting articulate (distinct) speech are exceedingly complex, as may be seen from an inspection of the full-page halftone opposite page 467. Because of this complexity it is impossible to transmit speech by means of discontinuous waves (Fig. 541). The parts of the voice lost because of the gaps between the wave

* Crystal detectors are now superseded by vacuum tubes for both wireless telegraphy and wireless telephony.

trains would render the language unintelligible. Therefore speech is transmitted on continuous, or "carrier," waves

FIG. 541. A series of wave trains

(Fig. 542) having a frequency (radio frequency) above the limit of hearing. The production of continuous waves will be discussed later (p. 598).

FIG. 542. Continuous, or carrier, waves of radio frequency

At the sending station the continuous waves (Fig. 542) are "modulated" by the voice at the microphone; that is, the sound waves of the voice act upon the apparatus in such a way as to alter the otherwise uniform amplitude of the continuous waves (Fig. 543). These modulated carrier waves

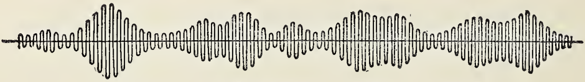


FIG. 543. Modulated radio-frequency waves

on reaching the aerial of the receiving station produce corresponding oscillatory currents in the wires of the aerial. By means of a crystal or a vacuum tube, the oscillatory currents are rectified into a series of *unidirectional* electric currents, or pulses, somewhat after the manner indicated in Fig. 544 (*a*). These variable pulses are used to operate a tele-

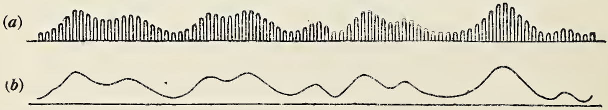


FIG. 544. (*a*) Rectified oscillations and (*b*) audio-frequency variations

A Historic Scene — the Earliest Use (1917) of the Wireless Telephone in Aviation

One of the most notable developments of the World War was the directing of a squadron of airplanes in intricate maneuvers by wireless telephone, either from the ground or by the commander in the leading plane. The upper picture shows the pilot and the observer conversing with a special apparatus designed to eliminate plane noises, and the lower picture shows President Wilson talking to airplanes. (See the next page)

Wireless Telephony

The telephone encircles the globe. In 1936 the American Telephone and Telegraph Company and associated companies provided regular wireless-telephone service to all parts of the world through the channels indicated above

phone receiver or, after amplification, a loud-speaker. The vibrations of the diaphragm of the telephone receiver or of the cone of the loud-speaker follow the top of the curve in Fig. 544 (*a*), as indicated in Fig. 544 (*b*), and thus reproduce faithfully the original sound waves at the distant transmitting station. These audio-frequency vibrations rarely go outside the limits of 20 to 8000 vibrations per second.

A receiving circuit. Fig. 545 represents a *regenerative* receiving circuit capable of receiving long or short waves. When the modulated waves (Fig. 543) reach the tuned aerial of the receiving station, they develop therein feeble electrical

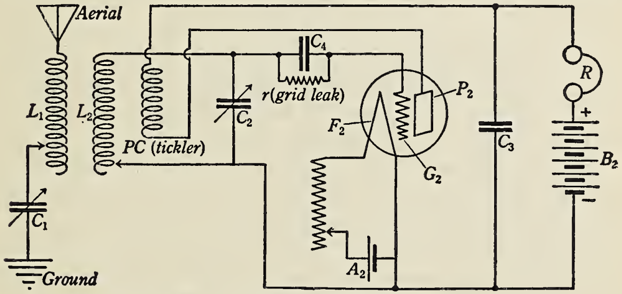


FIG. 545. A regenerative receiving circuit

oscillations which induce oscillations in L_2 of the tuned grid circuit. This varies the potential of the grid G_2, thus causing corresponding changes in the strength of the electronic current flowing from the incandescent filament F_2 to the plate P_2 and thence back through the plate coil *PC*, or *tickler*, through the phones to the filament. The tickler is so placed that the current variations in it react inductively on the coil L_2 to strengthen the original grid-circuit current. This intensifies the variations in potential at the grid, which in turn intensifies the variations in strength of the electronic current from filament to plate, and this still further intensifies the variations in potential at the grid, and so on up to a point where the resistances of the circuits prevent further increase. This is the

well-known *regenerative principle*, by which very feeble oscillations produced by the incoming waves may be amplified and then used to intensify the original oscillations. *The energy for regeneration comes from the battery B_2.*

When the tube is in use, the grid and the grid condenser C_4 tend to accumulate a negative charge which, as we have seen (p. 579), would tend to block completely the action of the tube. Therefore a high-resistance grid leak r is shunted around the condenser C_4 to permit the comparatively slow return of the accumulated electrons to the filament F_2 by way of r and L_2. The grid condenser and grid leak serve, therefore, as a variable potential, or "C bias," and cause the tube to act as a detector, or rectifier, of the radio-frequency waves. The tube not only serves in place of a crystal detector (D, Fig. 539) but also amplifies, or strengthens, the signals, since a small potential on the grid serves to control the comparatively large currents of the local battery B_2.

The telephone receivers, or the audio-frequency transformer used in their place in the circuit when still further amplification of the signal is desired (see AFT, Fig. 546), contain thousands of turns of very fine wire wound upon iron; and, because of the consequent *choke-coil* effect, or impedance, of these coils for *high-frequency* changes in current strength, the *radio*-frequency variations (Fig. 543) of the plate current pass largely by way of the condenser (Fig. 545), while the slower *audio*-frequency variations (Fig. 544) of the plate current pass readily through the receivers to actuate the diaphragm.

The "Triode" detector tube (Fig. 527), as well as the diode, or two-electrode Fleming valve, is used in modern receivers, but the regenerative feature is obsolete, since with it the circuit may be made to oscillate easily by bringing the tickler coil too close to the coil L_2. The receiving set then becomes a small transmitting station, generating continuous waves. The waves sent out from the aerial are very weak, but are nevertheless distinctly audible in other neighboring receiving sets. This causes annoying interference with the reception of broadcast programs.

Receiving circuit with detector and radio-frequency and audio-frequency amplifiers. Fig. 546 shows a receiving circuit that does not oscillate, yet gives amplification of the received waves through the use of three vacuum tubes instead of one. As in Fig. 545, the oscillations set up between the aerial and the ground induce similar oscillations in the grid circuit of T_1, this circuit being tuned by means of C_5. T_1 has no grid condenser (like C_4 of Fig. 545), and in its plate circuit is the coil L_5 instead of telephone receivers. This coil has a low impedance; hence radio-frequency oscillations flow through it, much stronger than those in the grid circuit. T_1 thus becomes

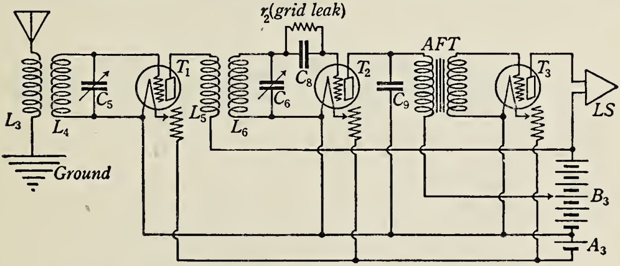


FIG. 546. Receiving circuit using radio-frequency and audio-frequency amplifiers

a *radio-frequency amplifier.* The oscillations in L_5 induce similar ones in L_6 and the grid circuit of T_2, which is tuned by means of C_6. T_2 acts like the tube of Fig. 545, except that the regenerative coil *PC* is not used. T_2 is called the *detector,* or *rectifier,* because it changes the radio-frequency oscillations to audio-frequency pulses, as explained on page 577. These audio-frequency pulses flow through the primary of the audio-frequency transformer *AFT*. This transformer has an iron core, as indicated by the vertical lines between the coils. The secondary of *AFT* is connected to the grid of T_3, which then becomes an *audio-frequency amplifier.* That is, the audio-frequency pulses coming to the grid of T_3 cause similar, but much stronger, pulses to flow in the plate circuit. They are

strong enough to operate the loud-speaker *LS* and thus be heard in all parts of the room. The same filament battery A_3 and plate battery B_3 are used for all the tubes, except that only a part of B_3 is used for the detector tube. Modern receivers do not usually use batteries for A_3 and B_3 in Fig. 546.

The superheterodyne receiving circuit. Many different receiving circuits have been employed, but one of the most important is the so-called *superheterodyne* circuit, invented by Armstrong. This circuit is shown schematically in Fig. 547. A small continuous-wave generator, or "local oscillator," produces a frequency which differs from that of the incoming signal frequency by an amount greater than that which the

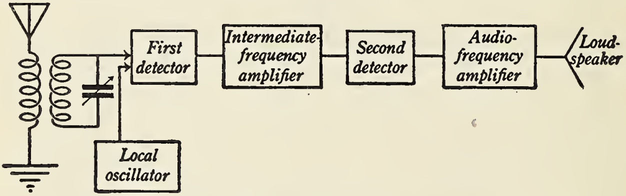


FIG. 547. The superheterodyne receiver

ear can detect, above 20,000, say 175,000. When the local and signal frequencies are combined in the so-called first detector tube, a beat note results at this superaudible, or "intermediate," frequency of, say, 175,000. After this has been amplified, a second detector tube isolates the original audio frequency. This audio-frequency is usually amplified before being used to operate a loud-speaker. In tuning this circuit to a different station it is necessary to adjust both the tuning circuit and the local oscillator for the received signal so that the beat frequency between these two will be constant. By this means the intermediate-frequency amplifiers may be built so as to amplify only one frequency. Thus not only great selectivity but high amplification can be obtained.

The modern home receiving set. Thus far we have considered circuits in which the power comes from banks of bat-

teries, but in modern practice it is generally the house-lighting current that furnishes the power. This, however, is usually alternating current, which, if used to heat the filaments of the radio tubes directly, would cause a pronounced hum in the loud-speaker. Therefore nearly all modern receiving tubes employ a cathode consisting of a cylinder which is heated indirectly by the radiation from an enclosed alternating-current filament. Further, the direct current necessary for the direct-current field between filament and plate is usually furnished by an ordinary two-element vacuum-tube rectifier (Fig. 548), and there is a filter to smooth out the fluctuations. Such a filter consists usually of an arrangement of capacity and inductances like that shown in Fig. 549. The fluctuating direct current coming in from the left has practically all its ripple taken out by the time it gets through the second choke and condenser system. Each choke usually has an inductance of from 15 to 30 henrys and each condenser a capacity of about 8 microfarads.

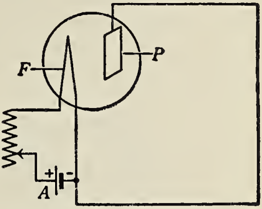


FIG. 548. A vacuum-tube rectifier

Directional receiving. Although an aerial connected with the ground through a coil and condenser or a coil alone, as in Figs. 545 and 546, is still the most common type of receiving system, the so-called loop aerial (Fig. 550) is used when it is important to locate the direction of the sending station. The loop consists of a few turns of wire wound on a frame generally about 3 feet in diameter. When the loop is so

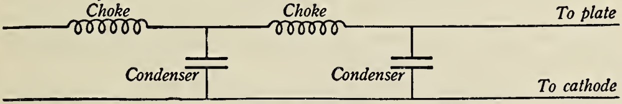


FIG. 549. A filter

turned that its edge points toward the transmitter, and the condenser is adjusted so that the receiving set is in tune with the transmitting set, an alternating current is induced in the loop circuit. When, however, the face of the loop is turned toward the transmitter, no current flows, since the currents that tend to be induced in the right and left halves of the loop now oppose each other. This type of receiver, then, enables one to determine quite accurately the direction from which the radio waves are coming. This is the basis of the radio compass, used to direct ships and airplanes.

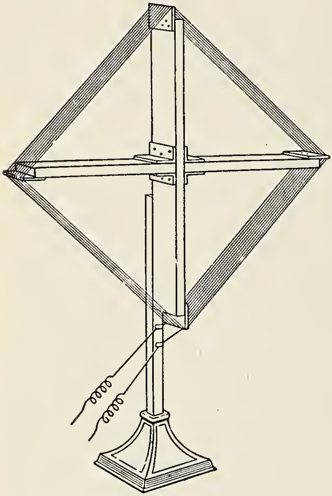
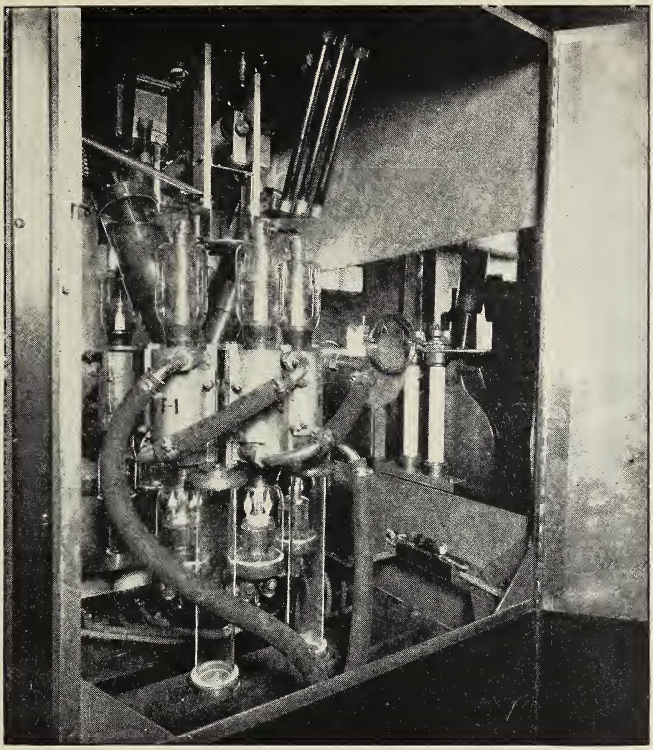


FIG. 550. A loop aerial

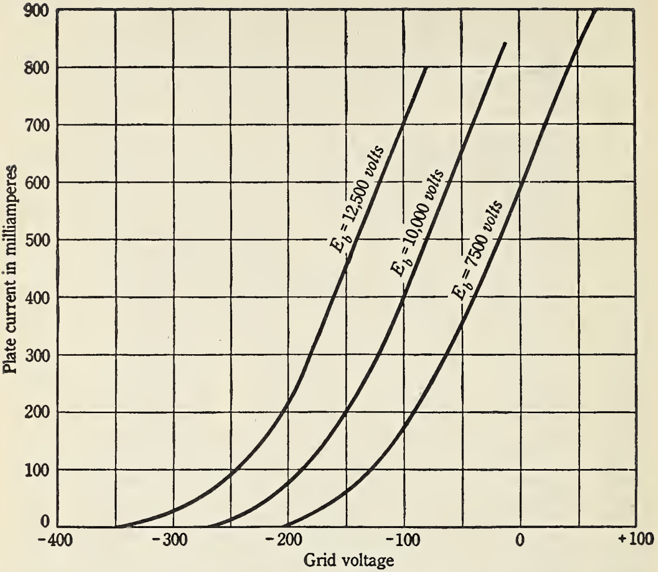
The transmitting station. Not only is the vacuum tube used at the receiving station in the variety of ways just described, but it is now being used at the transmitting end, practically exclusively, as a *generator of oscillations* varying over an extremely wide range of frequency. The Federal Communications Commission assigns to each broadcasting station a definite frequency for the carrier wave on which it must operate. The principle used in the production of these carrier waves is as follows:

By increasing the coupling between the tickler coil and the coil L_2 of Fig. 545, the regeneration, or return of energy from the battery B_2 to the grid, may be made so effective that the resistance losses are more than balanced. Then the current in the grid circuit oscillates at a frequency which largely depends on the size of L_2 and C_2. Transmitting stations equipped with this or similar vacuum-tube oscillators are



Transoceanic Short-Wave-Telephony Installation

This is a bank of six 10,000-watt water-cooled tubes, connected in parallel, as used in modern short-wave transoceanic telephony. It is capable of operating up to 30 megacycles, or 30,000 kilocycles (10 meters wave length). For telephoning from the United States to Asia and South America this short-wave system is exclusively used. For telephoning to Europe the telephone company uses both the short-wave and the long-wave system, the latter employing a wave length of 5000 meters (60 kilocycles). When one type fails, the other usually "gets through," so that the service is seldom interrupted by weather conditions. World-wide telephony is possible only because of the Kennelly-Heaviside layer, which prevents the energy from passing out into space. (Courtesy of the Bell Telephone Laboratories)



Characteristics of the Vacuum Tubes Shown opposite Page 598 (Three-Electrode Filament Types, Water-cooled)

The graph shows the electronic characteristics of each of the giant 10-kilowatt water-cooled short-wave tubes. The current through the heating filament is 41 amperes, and the potential fall across the filament terminals is 21.5 volts. The average life of such a filament is 1000 hours. The voltage that drives electrons from the filament through the grid to the plate may be as high as 17,500 volts. When the tube is working normally at 10,000 volts between filament and plate, a negative potential of — 50 volts is applied to the grid to keep the tube working on the straight part of its characteristic. (See page 579.) The graph then shows that the mean electron current passing from filament to plate through the grid is about 650 milliamperes. The graph also shows that if the tube is working at a plate potential (E_b) of 12,500 volts, to work upon the same portion of the characteristic just considered requires a negative grid potential of a little more than — 100 volts. In this tube the plate is the copper cylinder in the center surrounded by the water jackets through which water circulates at the rate of 2 gallons per minute

operated commercially in the frequency range from 50,000 to 300,000,000 cycles per second (wave lengths 6000 meters to 1 meter). They radiate from a fraction of a watt to as high as 150,000 watts. The lower-frequency and higher-power stations are used in general for long-distance commercial radio telegraphy. The range of frequency used for broadcasting stations is from 550,000 to 1,500,000 cycles per second (wave lengths 547 meters to 200 meters). Higher frequencies than these are used for short-wave commercial telephony, for communication with airplanes, and for many other purposes.

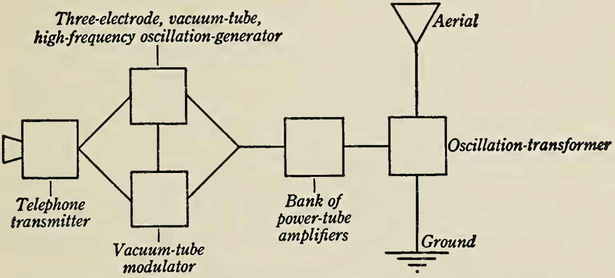


FIG. 551. High-power, long-distance, wireless-telephone transmitting station

¶ It is entirely beyond the scope of this book to explain the complex details of a wireless-telephone transmitting station. However, a method used at present in high-power long-distance transmission is indicated in Fig. 551 and may be outlined as follows: Air vibrations produced by the voice make variations in the current of the primary circuit of the telephone transmitter. This induces corresponding E.M.F.'s in the secondary circuit, which impress audio-frequency variations of potential upon the grid of a vacuum-tube modulator. The resulting changes of audio frequency in the current of the plate circuit of the modulator correspondingly affect the output of the high-frequency oscillation-generator. This modulated radio-frequency output is amplified by a bank of

three-electrode power tubes and is then delivered to the aerial through an oscillation-transformer. Although trans-oceanic telephonic communication has been successfully and repeatedly accomplished since 1915 (see opposite pages 578 and 593), regular commercial service was not established until January 7, 1927.

[**The Kennelly-Heaviside layer.** Radio waves are electromagnetic waves and are similar to light in their nature, except that they are of a much lower frequency. It is possible to use radio waves to signal around the earth and beyond the horizon, because there exist in the upper atmosphere several layers of ionized gas forming the so-called *ionosphere.* These layers, the lowest of which is called the Kennelly-Heaviside layer, reflect back to the earth radio waves which would otherwise be lost in space. This Kennelly-Heaviside layer can be thought of as a gigantic mirror which reflects the radio waves back to the earth. If, however, the frequency of the radio waves is too high, then they act more like light waves and are not returned to the earth. Ultra-high-frequency radio waves of frequencies higher than 60,000,000 cycles per second (wave length 5 meters) can be used for reliable communication at distances not greater than about fifty miles.

[**New types of vacuum tubes in radio communication.** The enormous advances in the field of radio communication in the last decade have been due primarily to the use of vacuum tubes. As already indicated, the vacuum tube has been developed as a generator of continuous high-frequency oscillations, as a detector of these oscillations, as a modulator to modify the continuous oscillations by means of voice frequencies, and as an amplifier at both audio and radio frequencies. The vacuum tube has completely replaced all former devices used for any of these purposes. On account of the many functions of vacuum tubes, a large number of special tubes have been developed. For the newest type of transmitting tube see opposite page 579. At the receiving end the three-element tube has been largely displaced by more complicated tubes developed for special purposes. The

four-element tube, or screen-grid tube, has been developed as an amplifier for high frequencies. This tube is the same as the ordinary three-electrode tube, save that an extra grid which is positive with respect to the filament is placed between the control grid and the plate, in order to act as an electrostatic shield between these two electrodes. This screen grid reduces the capacity between the control grid and anode and allows the tube to function much better as a high-frequency amplifier. The *pentode* is like a screen-grid tube but with still another grid between the screen grid and the anode. The function of this extra grid, which is called a suppressor grid, is to prevent electrons from leaving the plate and going to the screen grid. The suppressor grid is usually connected directly to the cathode. By its use the tube operates over a greater range of voltage to handle more power than the four-element tube. The pentode is commonly used as an audio-frequency amplifier in the last stage of a radio receiver where considerable power is desired. Numerous other tubes, having as many as five grids or more, have been developed for special functions. These tubes, however, are in general combination tubes which perform more than one function in the same container. It is beyond the scope of this book to describe their operation.

[Another development in receiving tubes is the all-metal tube. This contains small beads of special glass to insulate the lead-in wires. This glass is joined to the iron shell by means of eyelets made of an alloy called "Fernico" (iron, nickel, cobalt). Such tubes permit close and more accurate spacing in their construction, are smaller in size, and furnish complete shielding from outside electrostatic effects. They are particularly useful for work at high frequencies.

Summary. The discharge of a Leyden jar or other like condenser is in general oscillatory and therefore sends out ether waves of very high frequency (of the order of a million a second).

The carrier wave in wireless is a continuous high-frequency wave.

In wireless telephones speech frequencies are superposed upon such a carrier wave.

These audio frequencies superposed upon the carrier wave are reproduced as audio frequencies on reaching the loud-speaker of the listener.

The carrier waves are usually generated by vacuum-tube oscillators.

The receiving system involves the action of rectifiers, detectors, radio amplifiers, and audio amplifiers.

Radio waves are like light waves, except for their wave length.

Directional receiving uses a loop antenna.

QUESTIONS AND PROBLEMS

1. Why are wireless waves called hertzian waves?

2. How does a crystal detector work?

3. How does a three-electrode-tube detector work?

4. What are the essential elements of the superheterodyne receiver?

5. How is a regenerative electron-tube circuit set up?

6. What is the difference between a radio-frequency amplifier and an audio-frequency amplifier?

7. (*a*) What is the Kennelly-Heaviside layer, and (*b*) how does it affect radio transmission?

8. Explain the principle underlying directional receiving.

9. What is the function of the filter in a home receiving set?

CHAPTER XXIII

Relation between Electrons and Radiation

Photoelectric Effects

Large-scale and small-scale effects. Up to about 1900 the laws of physics, such, for example, as Newton's laws of motion, had been discovered through the study of large-scale effects, so-called *macroscopic* phenomena. It was only after the discovery of the electron in the last decade of the nineteenth century that it began to be possible to peer inside the atom and learn how individual electrons behave. In this new field of so-called *microscopic* phenomena it was at first assumed, and quite naturally, that the old laws would hold; but in some instances, at least, this has not been found to be true. This in no way casts doubt upon the validity of the older physics, which is just as valid as ever *for the range of phenomena in which it had been experimentally tested*, that is, for all large-scale effects, such as are dealt with in all kinds of engineering. Outside this range, however, we must depend wholly on new experiments to find the new laws that prevail. Some of the most interesting and important of these newly-discovered laws of electronic physics came from a study of the photoelectric cell.

The photoelectric cell. A photoelectric cell of the type commonly used is shown in Fig. 552; it consists of a vacuum bulb inside of which there is a central metal rod A, called the anode, and a curved metal plate C, called the cathode. The cathode, or "sensitive" surface, is made of silver coated with a thin layer of cesium and its compounds. Other substances than cesium on silver have been used for the cathode, as, for example, potassium and potassium combined with hydrogen

supported on the inner walls of the glass bulb. The anode is connected to the positive terminal of a battery, as shown in the figure. If now a beam of light is allowed to enter the cell and fall on the sensitive surface, it is found by experiment to detach negative electrons from this surface, so that an electron current flows to the anode *A* and through the circuit of the battery and the galvanometer. These electrons are called photoelectrons because they are released by the influence of light (Greek *phos* (*photos*), "light"), and currents produced in this way are called photoelectric currents.

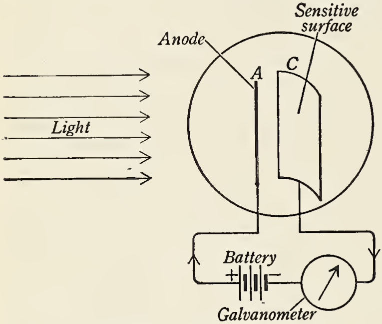


FIG. 552. A photoelectric cell

There are three important laws of photoelectric action. The first is that the strength of the current, that is, the number of electrons released, is strictly proportional to the intensity of the light falling on the cesium. This law is very important for many practical applications of the photoelectric cell. The second purely experimental law is that the energy of emission of each individual electron is independent of the intensity of the light falling on it. The third experimental law is that this energy of emission is proportional to the frequency of the incident light. These last two laws are of great theoretical significance. (See page 608.)

The photoelectric cell in sound motion pictures. The proportionality between light intensity and current produced makes the photoelectric cell a vital element in the sound-motion-picture industry. Thus, when a narrow beam of light is focused on a sound track (see opposite page 481), either a variable-density track or a variable-width track, the light that is transmitted through the track and then falls on the photoelectric cell generates in that cell electron currents which

vary in strength exactly as the light varies in intensity. These currents, therefore, possess precisely the same wave form as the original currents, the variations of which made the sound track. The currents from the photoelectric cell are then amplified and sent to a loud-speaker, which faithfully reproduces the sounds which originally fell upon the microphone. The extraordinary fidelity of this reproduction is familiar to all who have attended sound motion pictures.

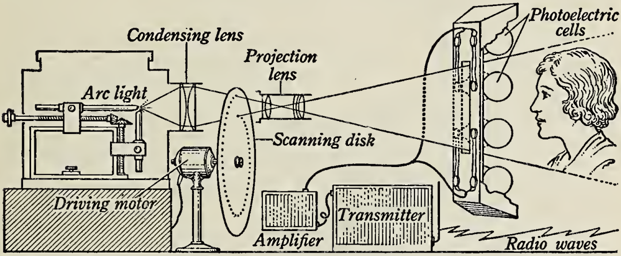


FIG. 553. Television transmitter

[**The photoelectric cell in television.** Through improvements in the photoelectric cell television is today scientifically an accomplished fact. Whether it will be commercially successful or not depends merely on whether the public wants it enough to pay what it costs.

[All television schemes use some kind of so-called *scanning* device. In one of the well-known television methods a "Nipkow" disk is used to scan the scene. This consists of a circular disk rotated by a motor (Fig. 553) and pierced with a spiral of fine holes through which pass narrow pencils of light to sweep in succession over all points of the face (or scene) that is to be transmitted. The entire face is thus successively illuminated in horizontal streaks during one revolution of the disk, a time which is less than the persistence of vision, say one tenth of a second. The light beam is reflected from the face to adjacent photoelectric cells in larger or smaller amounts according to the brightness or darkness of the region

it falls upon. The photoelectric cell then faithfully transforms these varying intensities of light into corresponding photoelectric currents.

[When these currents arrive at the receiving, or seeing, end, they go through a neon lamp (Fig. 554) or other source of light which glows with an intensity proportional to the strengths of the currents going through it. The light from this glowing lamp is then sent through a second scanning device which is

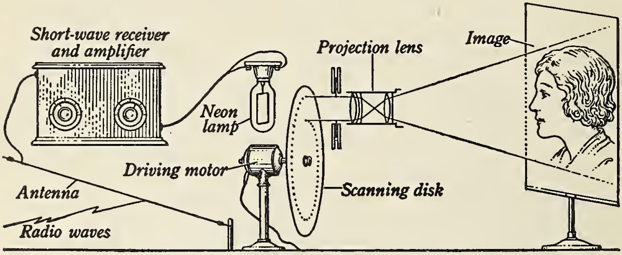
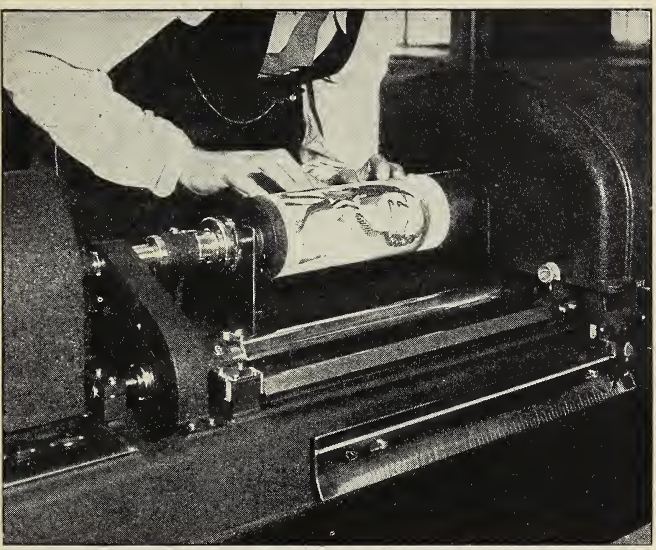


FIG. 554. Television receiver

exactly similar to that at the sending end and runs synchronously with it. This scanner reassembles on the receiving screen all the points of the original face (or scene) in just the relations they bore to one another there, so that the eye and the brain of the observer perceive the scene as a whole. This would of course be impossible save for the persistence of vision, which makes all the images of the points appear to be on the retina simultaneously, though they actually arrive in succession. The foregoing description applies in its essentials to all systems of television.

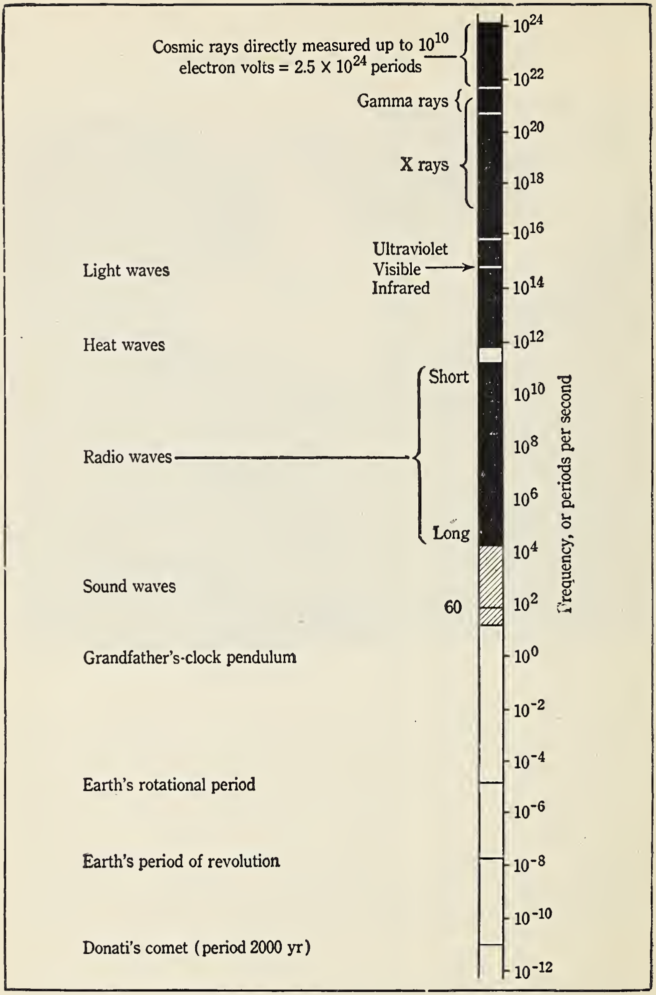
[The transmission of pictures by wire is a process essentially like television, except that the persistence of vision is not here involved, so that the scanning can be done as slowly as is desired. The details of the process can be understood from the illustration opposite this page.

[**Proof that the energy of ejection of photoelectrons is independent of intensity and proportional to frequency.** Suppose



Transmission of Pictures by Wire

A photographic print is being placed on the cylinder of the wirephoto sending machine. This cylinder revolves at the rate of 100 revolutions a minute and moves laterally at the rate of 1 inch a minute, thus successively subjecting each small element of the picture to a small beam of light. The reflection from this beam of light falls upon a photoelectric cell. This cell then sends out over the wirephoto circuit currents which possess variations in intensity corresponding exactly to the variations in the light reflected from the white and dark points of the picture. These currents in turn actuate a slit, or light valve, which admits light to a photographic film placed on a similar synchronously running cylinder at each distant receiving station. The portrait of Alexander Graham Bell opposite page 434 was so transmitted. (Courtesy of the *Los Angeles Times*)



Frequency Spectrum

that the light entering the photoelectric cell in Fig. 552 is monochromatic (of one color) — for example, the green light of the mercury arc. If the battery in that figure is reversed, no current is found flowing through the galvanometer, since experiment shows that negative electrons alone are detached by light from metals.

[But if the potential of the battery, reversed as just indicated, is say a volt or less, a small negative-electron current will be found to flow to the central rod. This is because the light ejects these negative electrons from the cathode with an energy sufficient to carry them against the opposing electrical field to the anode so long as this field is not too strong. Then, by varying this reversed (or retarding) potential until the negative-electron current to the rod just ceases, we can measure the maximum energy of emission (in volts) of these negative electrons ejected from the cathode under the influence of the green mercury line. We can then see how this maximum energy of ejection of the individual electrons varies with the intensity of the light by removing the source of light to three times its distance from the cell. The intensity of the light will then be one ninth as great.

[When the German physicist Lenard first tried this experiment, in 1900, he was astonished to find that this *energy of emission was altogether independent of intensity*. Thus, though at a distance of 1 foot a given source of light did indeed release a *number* of electrons (that is, produce an electron current) nine times as great as it released at a distance of 3 feet, the *energy* of emission of each individual electron was the same for both distances of the light.

[This effect was surprising because it was to be expected from a corpuscular theory or from any kind of "localized-energy theory," but not from a spreading-wave theory of light. Thus, if a certain number of "rays of light" are sent out as light darts, or linear wave trains, from a source of light, it is quite clear that nine times as many of these rays will hit a target of given size, say 1 square centimeter, when the light is

1 foot away as when it is 3 feet away. (See Fig. 438, p. 493.) Only when the energy of the light remains localized in the rays, or lines, of light may we expect it to transfer the same kinetic energy to an electron, whatever the distance. But this is just what Lenard's experiment showed was the case. Later experiments by other observers, Ladenburg, Hughes, K. T. Compton, and Millikan, who let monochromatic light of widely different frequencies enter the photoelectric cell, showed that the energy of emission of individual electrons under the influence of different frequencies is directly proportional to these frequencies. It was 1915 before this relationship was definitely established, though Einstein suggested it as early as 1905.*

[**The photon theory of light.** Experiments of the foregoing sort have now led us to account for all photoelectric effects by just such a light-dart, or photon, theory as has been suggested above. Each individual photon, or light dart, is assumed to carry the energy $E = h\nu$, in which h is merely the universal proportionality constant connecting energy E and frequency ν as measured by the methods presented on pages 607 and 616. In photoelectric absorption the whole of this incident energy $h\nu$ is assumed to be transferred to one electron. This electron is then emitted with the whole of the energy $h\nu$ less the amount of energy necessary to detach it from the metal. (ν is the Greek letter nu.)

[In the hands of A. H. Compton of The University of Chicago this photon theory has had remarkable success in accounting for the absorption of X-ray photons by individual *free* electrons. He assumed that in the encounter of a photon with a free electron the laws of impact are essentially those of two elastic spheres, so that the laws of the conservation of energy and the conservation of momentum hold true. He was then able to explain with accuracy some important effects observed in the scattering of X rays.

* See Robert A. Millikan's *Electrons (+ and −), Protons, Photons, Neutrons, and Cosmic Rays* (University of Chicago Press), Chap. 10, for the history of this development.

Photons versus waves. The net result of all these experimental findings of the last twenty years is that the photon theory of light is now quite universally accepted by physicists as a correct way of picturing an individual light ray. Indeed, we find that we must use it whenever we are dealing with an individual "elementary process," that is, a microscopic event. On the other hand, whenever, as in studying interference effects, we are dealing with a huge ensemble of elementary processes, — that is, a statistical array of microscopic events which taken together constitute a large-scale phenomenon, or a macroscopic event, — we find that we must use the wave conception in order to predict the facts of observation. Just why this is so may not as yet be entirely clear to anyone, but it is at least the present status of the *experimental* situation. All the ether-wave theory, then, that we learned in Chapters XVIII–XX is just as valid now as it has ever been. It is just as useful, indeed indispensable, for correlating and interpreting the facts of optics there studied; and in the field of wireless it fits all the facts perfectly. It fails completely, however, when we begin to study the act of the absorption, scattering, or emission of radiation by an individual electron. It was in the photoelectric cell that we first began to study such elementary processes (microscopic events), and we owe to it the great discovery that *electromagnetic radiation itself, when looked at sufficiently minutely, has in fact a discrete,* or photonic, structure,* each individual photon carrying an energy $h\nu$, where ν is the photon's frequency as measured by the methods of Chapters XVIII–XX.

The case is altogether analogous to that found in the history of electricity. We learned by far the greater part of all that we know now about electricity before we knew or needed to know anything about the discrete, or electronic, structure of an electrical charge, and we did not have to forget any of this knowledge when the electron was discovered. So with light: the photon theory does not displace the wave theory; it merely supplements it. *The wave theory tells us how the*

* Made up of separate parts, or distinct units.

photons distribute themselves when we have a large number of them to deal with.

Summary. In a photoelectric cell (1) the number of electrons detached by the light is proportional to the intensity of the light; (2) the energy of emission of the electrons is independent of light intensity, (3) but directly proportional to frequency.

The first condition above makes possible sound motion pictures, for it is essential to the operation both of the variable-density sound track and of the variable-width sound track. The first condition is also one of the essential elements in television. A second condition of television is a synchronously operating scanning device both at the transmitting and at the receiving end.

The second and third conditions above are fundamental for the photon theory of light. All electromagnetic radiation when looked at sufficiently minutely is thought to have a discrete, or photonic, structure. The photon theory, however, does not displace the wave theory; it merely supplements it.

QUESTIONS AND PROBLEMS

1. What experiment shows that photoelectron energies are independent of light intensity and proportional to light frequency?

2. How does a variable-density sound track reproduce speech?

3. What general principle underlies all "scanning"?

4. Why do we think that individual light rays have a discrete, or photonic, structure?

5. What kind of effects do we still explain by the wave theory?

Atomic Structure

[The Wilson cloud chamber. The Wilson cloud chamber rivals the vacuum-tube amplifier and the photoelectric cell in the amount of new information it has given us about the world in which the electron lives, and how things happen in that world. It was first used by C. T. R. Wilson of Cambridge, England, in 1910 and 1911. A modern form, with which all the cosmic-ray photographs herein found were taken, is shown in Fig. 555. The chamber contains air or any other

gas saturated with the vapor of water or alcohol. The piston is very suddenly pulled to the right by a solenoid not shown in the figure. The gas in the chamber, cooled by this expansion, becomes thereby supersaturated and hence tends to condense. If there are no free ions or particles of dust in the gas, the condensation takes place on the walls of the chamber. If within say a hundredth of a second after this expansion an alpha particle or a beta particle from radium shoots through the chamber, knocking electrons out of a whole series of

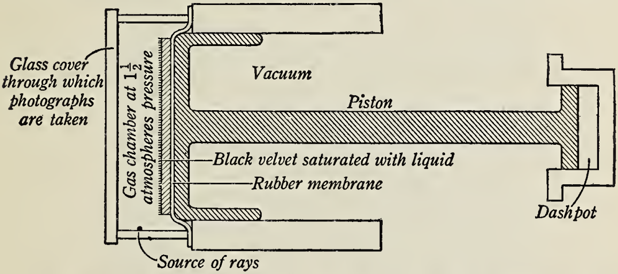


FIG. 555. The Wilson cloud chamber as used by Carl Anderson and Seth Neddermeyer for photographing cosmic-ray tracks. For this purpose the chamber is placed vertically in a very powerful horizontal magnetic field

atoms along its path, each of the charged particles (ions) thus produced acts as a nucleus for the condensation of the vapor. Each ion becomes at once the center of a droplet, so that the actual path of the alpha or beta particle becomes visible by means of light reflected from this series of droplets. These droplets may be so close together that the individual droplets do not show, and one sees only a white streak (black streak in the print opposite page 613). This is the actual track of the alpha or beta ray.

[It is altogether remarkable how much information about the structure of the atom has been obtained by studying photographs taken in this way.

[**The mass of the atom concentrated in the nucleus.** From the photographs of alpha-ray tracks shown on the opposite

page some of the most important properties of the structure of the atom can be at once inferred. Thus:

1. The fact that the tracks are there at all proves that the neutral atom has electrical charges as constituents, for it is the existence of these charges, knocked out of the neutral atoms, that causes the condensation. If electrons did not exist within atoms, there could be no tracks.

2. The straightness of the tracks shows that the electrons, jarred loose by the passage of the alpha ray and left scattered along the tracks in great numbers (as many as 20,000 of them per centimeter length of track), are exceedingly light objects in comparison with the alpha ray. The alpha particle brushes the electrons aside without being any more deflected by them than a bullet would be deflected by a swarm of gnats.

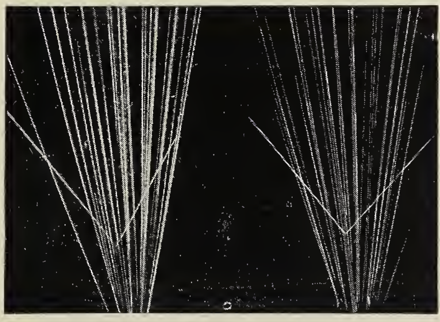
3. The fact that the tracks do show occasionally a sudden sharp deflection proves conclusively that there is within the atom a mass comparable to the mass of the alpha ray, a mass with which the alpha ray makes an encounter similar to the encounter between two elastic balls. In the upper photograph the colliding alpha particle is four times as heavy as the hydrogen nucleus. This is why it is deflected only a little from its original direction, whereas the hydrogen nucleus when struck shoots off with great speed to the left. In the middle photograph the colliding particles are exactly alike, and the striking body here shoots off at a large angle, as it should, the momentum being shared fairly equally between them. In the lowest photograph the nucleus which was struck is three and a half times as heavy as the alpha particle. Because of this large mass it acquires only a small velocity to the right, whereas the striking alpha particle rebounds with high speed sharply to the left.

Such deflections as these lend, then, the strongest of support to the view that the atom consists of a heavy, positively charged nucleus about which are grouped enough very light negative electrons to render the whole atom neutral.

The emptiness of the atom. The fact that the alpha particle, in order to make tracks of the length (8 centimeters)

A

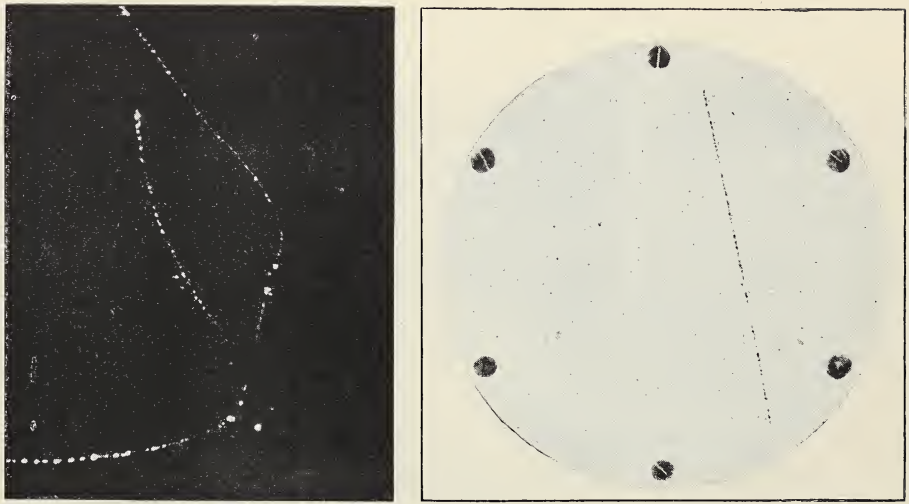
B



C

Blackett's Photographs of Alpha-Particle Collisions

A, with hydrogen atom; ***B,*** with helium atom; ***C,*** with oxygen atom



Photographs of the Tracks of Beta Particles Shooting through Air

The left panel is a photograph taken by C. T. R. Wilson of the track of a beta ray from radium. The right panel is a photograph taken in the Norman Bridge Laboratory of Physics at Pasadena, California, of the track of a negative electron, or beta particle, of very high speed. The particle was released by a cosmic ray and has an energy of 1.3 billion electron volts. Its curvature to the left can easily be seen. Such a particle shoots in practically a straight line through 20 centimeters of lead

shown in the photographs, must shoot right through at least 100,000 atoms without approaching near enough to a nucleus to suffer appreciable deflection, except at rare intervals, shows that this nucleus must be excessively small. Its diameter is estimated to be but 10^{-12} (.000,000,000,001) centimeter, or one ten-thousandth of that of the atom. The diameter of an atom is considered to be approximately the same as the diameter of the orbit of the most remote electron, namely, 10^{-8} centimeter. The nucleus is, then, no bigger with respect to this orbit than is the earth with respect to its orbit about the sun.

[When we look at beta-ray tracks, however, the emptiness of the atom is most conclusively demonstrated. In the photographs on the opposite page each individual droplet of water which condensed about an ion (formed an instant earlier by the passage of the ray at that point), can be seen as a distinct droplet. We can thus determine at once the mean distance the beta ray had to travel from the point at which it knocked an electron out of an atom to the point at which it knocked out another electron. Also, since we know the size of a molecule and the number of molecules per cubic centimeter, we can compute, as in the case of the alpha particle, the number of molecules through which a beta ray passes in going any given distance. The photograph on the right shows an extraordinary situation. When the computations were made, as above, this particular electron was found to have shot through as many as 300 molecules on an average before it came near enough to an electronic constituent of any of these atoms to detach it from the system and form an ion. This shows conclusively that the electronic or other constituents of atoms can occupy but an exceedingly small portion of the space enclosed within the atomic system. Practically the whole of this space must be empty to an electron going at this speed. Further, this great speed is responsible for the fact that the traversing electron is not bent from its path by its passage through the neighborhood of other electrons, which of course are no heavier than itself. But when the

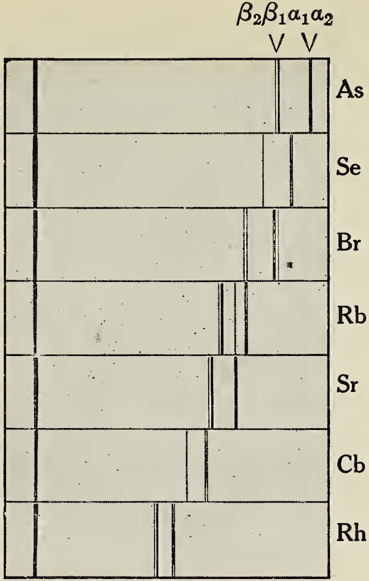
speed is less, this traversing electron, being very light, can easily be bent out of its course in the manner shown in the figure in the left panel.

Atomic numbers. In order that any atom may be electrically neutral, it is obvious that the number of negative electrons revolving about its nucleus must be, all told, just equal to the number of free positive units of charge, or positive electrons, which exist on the nucleus and by their attractions hold the negative electrons in place in their orbits. This number has been found by several different methods, one of which is as follows: When high-speed electrons are shot through an atom, they sometimes hit the electrons that are located within the atom and thus stimulate the emission of monochromatic waves, or rays, the frequencies of which can, in some cases, be measured by an ordinary spectrometer. This will be possible only if the stimulated waves happen to lie within the visible spectrum; but there is a quite similar instrument, called an X-ray spectrometer, which measures the frequency when the stimulated wave is of a frequency far above the visible.

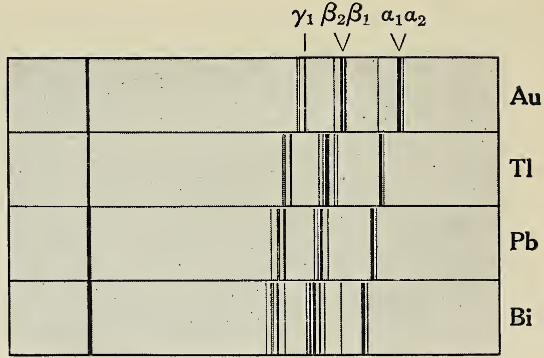
By thus shooting high-speed electrons into targets made of all sorts of elements, Moseley* first found in 1913 that the frequency of the X-ray line (the so-called $K\alpha$ line) thus stimulated in the atoms of the different elements moves up by 92 equal steps in going from the lightest element, hydrogen, to the heaviest element, uranium. Some of these steps, as experimentally measured, are shown in the figure opposite this page. Moseley himself did not fill in all these steps, but other experimenters have since done so, so that we are now justified in saying that we know just what element fits into every one of the possible steps from the lightest element, hydrogen, to the heaviest element, uranium.

The physical meaning of this relation is that the charge on the nucleus also moves up by 92 unit steps in going from hydrogen to uranium. We mean, then, by the *atomic number*

* A young British physicist who was killed in the World War when he was only twenty-four.



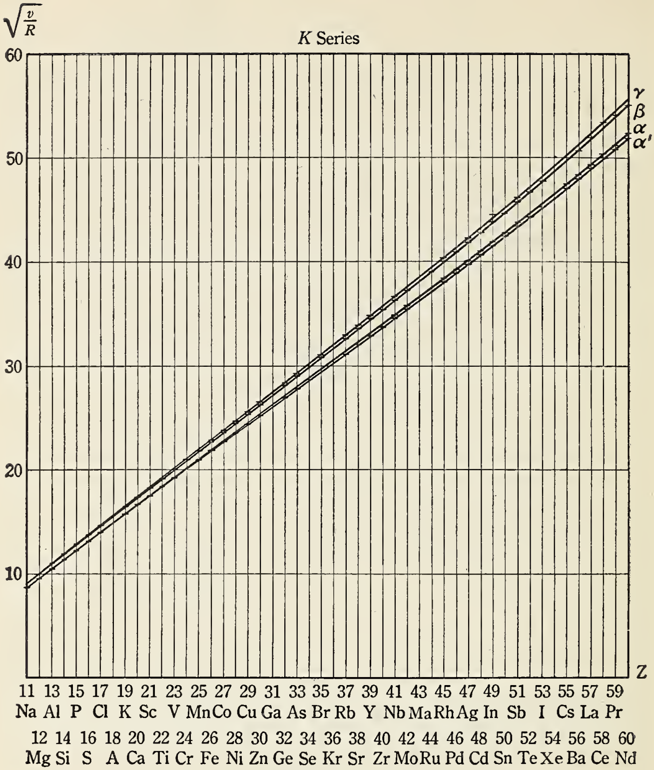
K SERIES



L SERIES

The remarkable element in these photographs is the exact similarity of the spectra produced by the different elements and the step-by-step shortening of the wave length (which is proportional to the distance from the line on the left to the spectral lines) as the atomic number *N* increases. This is shown both in the *K* series, which is produced by stimulating the inmost pair of electrons in each atom, and the *L* series, which is produced by stimulating the group of eight electrons in the second ring, or shell, from the center

Photographs of the Spectra of the Characteristic X Rays from Certain Substances (After Siegbahn)



Moseley's Law

This figure shows in graphical form the linear step-by-step progression of square-root X-ray frequencies, with atomic numbers. It is this relationship, now extending in 92 steps from hydrogen to uranium, that tells us that the physical world as we know it is built up out of just 92 elements, an element being defined as a body possessing a given nuclear charge, and therefore in its neutral state having a corresponding number of extranuclear electrons. Each element may have a number of isotopes, because the foregoing charge relations can be built up by combination of protons and negative electrons, or protons and neutrons (see page 622), that give different weights to the nucleus

of an element merely the number of unit positive charges on its nucleus, or, what amounts to the same thing, the number of unit negative charges that circulate about this nucleus. Thus the atomic number of hydrogen is 1, of helium 2, of lithium 3, of beryllium 4, of boron 5, of carbon 6, of nitrogen 7, of oxygen 8, of fluorine 9, of neon 10, etc., up to uranium 92. We shall learn, however (see "Isotopes," p. 624), that two atoms of lithium may have as different atomic weights as 6 and 7.

[**The location of the extranuclear electrons within the atom.** In the preceding paragraphs we discussed only the highest strong-frequency line that can be stimulated by shooting electron beams into atoms. But there are in fact a great many other frequencies so stimulated, and a study of these frequencies throws a great deal of light on where the electrons are located within an atom. The highest frequencies are, of course, given off by the electrons that lie closest to the nucleus and therefore are in the strongest electrical field. There are, in fact, just two of these innermost, or so-called *K*-shell, electrons in every atom except hydrogen, which of course cannot have two *K*-shell electrons, since it has only one extranuclear electron all told.

[But by shooting electrons into targets we also find another group of stimulated radiations of wave length seven or eight times the wave lengths of the so-called *K* series. This means that there is a group, or shell, of electrons that lie much farther away from the nucleus, where the electrical field is much weaker. There are, in fact, eight of these so-called second-shell, or *L*, electrons in all the heavier elements.

[By extending this method of experimenting we have found that all the electrons of the atoms of large atomic number are arranged in six different series of so-called shells, or levels, or orbits, which are known as the *K*, *L*, *M*, *N*, *O*, *P* levels, or orbits, situated at increasingly remote distances from the nucleus. The electrons in the outer levels are in very weak fields, and the stimulated radiations that come out from these levels are in many cases just the ordinary *visible* radiations. Indeed, all the so-called lines of the visible spectrum

are due to the stimulation of electrons that are in the weak electrical fields existing in the outer regions of the atom.

[**Measuring the frequency of photons in electron volts.** We have just been considering the process of shooting electron streams, or cathode rays, into atoms and thereby stimulating the emission of photons. This is just the reverse of the process that takes place in the photoelectric cell, in which photons enter the cell and communicate their entire energy to electrons, which are thus caused to fly out of the atom with great speed. The electron energy is then measured by finding how many volts of opposing electrical field must be applied to bring them just to rest. This latter process, of course, measures the energy of the electrons in electron volts (work done in moving an electron against an opposing P.D. of one volt), and the experiments with the photoelectric cells showed that this was proportional to ν, or equal to $h\nu$. When we are dealing, then, with an individual monochromatic light ray, we can get its frequency at once if we can measure its energy, and vice versa; for we know the value of the constant h. The actual number of volts required to stop an electron which has absorbed the full energy from a ray of sodium light of wave length .00005890 centimeter, or 5890 angstroms, is found to be 2.1 volts. Thus the energy of each photon of yellow sodium light is 2.1 electron volts. Similarly the energy of the photons constituting the ultraviolet line of wave length half that of sodium, namely 2945 angstroms, is 4.2 electron volts. The energy of the X ray line having a wave length of 1 angstrom is, then, 4.2×2945, or about 12,000, electron volts. These are the kind of X rays that are actually produced by the ordinary small induction coil, such as commonly develops a P.D. of about 12,000 volts. The energy of the X rays of very high frequency produced by shooting cathode rays into a tungsten target with an energy of 67,000 volts or more and thus stimulating the K shell in tungsten to emit its most prominent line, called its $K\alpha$ line, is 67,000 electron volts. In dealing, then, with individual rays of light or with electromagnetic energy of any wave length, the terms *energy* and

frequency are, in all respects save the units in which they are measured, completely alternative. A given frequency, as applied to a photon, means physically a given energy and nothing more.

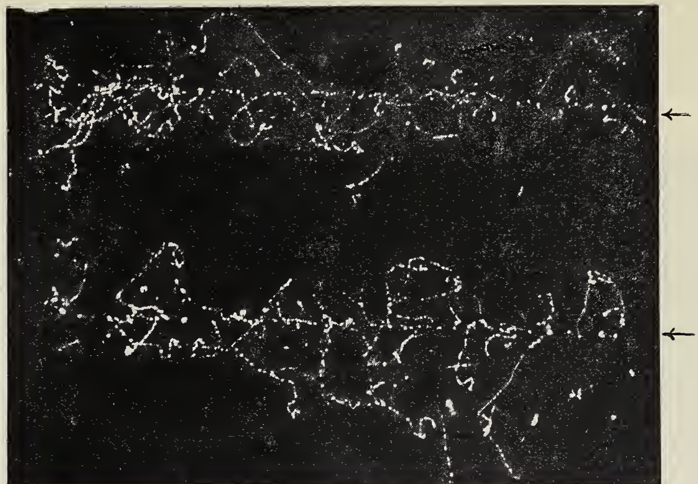
[**How atoms are stimulated to radiate photons.** It was formerly thought that the way in which atoms are brought to radiate was simply by having their various electrons or shells of electrons set into vibration in the different positions which they occupy within the atom; but such a conception of a static atom can no longer be entertained. The photographs opposite page 613 show that when a high-speed electron plunges through the atoms of a target it actually knocks some electrons out of these atoms; otherwise there would be no condensation of water droplets along the track. Suppose one of these detached electrons came from a K shell. This would leave a vacancy in that shell, and the attraction of the nucleus for all the extranuclear electrons would tend to draw a new electron from some more remote point into that vacant hole. It is assumed that a new electron, coming either from one of the outer shells or even from outside the atom, falls into the vacant hole. In so doing it changes its energy, and the difference $E_2 - E_1$ between its energies in the two levels is emitted as a photon of energy $h\nu = E_2 - E_1$.

[Or, again, the process by which the atom restores itself may be that an electron from the L level falls into the vacant hole in the K level. Then, an instant later, an electron from the M level falls into the vacancy which is now in the L shell, and so on, so that a whole series of lines is emitted. When a cathode beam shoots into a target and thus knocks electrons out of a great number of atoms, some of them will return to their normal condition by the full jump back from the outside of the removed electron (or another equivalent one), whereas other atoms will return by the series of smaller electronic jumps suggested above. For each one of the electron jumps a photon is emitted which carries away just the difference in the energy that the electron possessed in the two levels, that is, the level from which it came and the level to which it goes.

Each one of these photons of different energy appears as a definite spectral line in the spectroscope, no matter whether it is an optical spectroscope or an X-ray spectroscope. This is Bohr's explanation of the origin of spectral lines, such as those shown opposite page 614, and in the form herein stated it is now universally accepted by physicists.

❡The highest-energy photon that can be emitted under cathode-ray bombardment is evidently equal to the energy of the bombarding electron that was just able to knock the struck electron out of the atom. That is, if a 75,000-volt electron is shot into an atom and with that energy can just dislodge an electron that requires that much of a blow to dislodge it, when this electron returns it may radiate just that 75,000 electron volts of energy in the form of a single photon. Or, if it returns by several jumps, it will radiate several lower-energy photons, the sum of whose energy is again 75,000 electron volts. *To stimulate by cathode rays the emission of a spectral line of any frequency, whether it be of visible light or of X-ray light, requires an energy of the incoming cathode ray greater than the binding energy of the electron. The dislodgment of an electron from one of its normal levels within the atom gives rise to the line in question.*

❡The highest-frequency X-ray line that can be thus stimulated comes from dislodging one of the K-level electrons in the uranium atom. It has an energy of about 100,000 electron volts. However, radioactive transformations, representing, as they do, changes taking place within the *nucleus* itself, give rise to "spectral lines" of much higher energy than this, the highest being that of the gamma-ray photons (Fig. 522) spontaneously given off in the process of disintegration of the thorium atom. It has an energy of 2.6 million electron volts. It has been quite definitely shown that this is emitted the instant after the nucleus has emitted a beta-ray electron. It is natural to infer, therefore, that the emission of this beta ray left a hole in some kind of nuclear level and that a more remote nuclear electron then jumped in to fill this hole, emitting the gamma-ray photon of 2.6 million electron volts in



Photographs of the Tracks of Electrons Ejected by X Rays from the Molecules of Air

These tracks, with those on the next page, give convincing evidence of the photon theory. X rays enter through a narrow slit, indicated by arrows, and pass through thousands of atoms without making a hit; but when they do collide with an electron, they communicate to it their full energy. This electron makes a zigzag track because it is very light and is deflected by the forces existing between it and the electrons and nuclei of the atoms through which it goes

Beta-Ray Tracks

These beta-ray tracks were taken by C. T. R. Wilson of Cambridge, England. The electrons are photoelectrically released and hence receive the full energy of the incident photons, here fully 30,000 electron volts. When these photons are of sufficiently low energy, the electrons are thrown out at right angles to the direction of the incident photon (see opposite page 618); but as the energy increases, the electron tracks are longer and straighter and tend to take on a stronger and stronger forward component, as here shown. The X-ray beam was here a very narrow one, passing from right to left in a line at the middle of the figure (see the arrow)

so doing. This was the highest-energy photon known before the discovery of cosmic rays.

[**The photoelectric effect with X rays.** Having found how X rays are produced by shooting cathode rays into the atoms of a target, we next ask what happens to the atoms of any substance through which we shoot a beam of such X-ray photons. The Wilson cloud chamber gives us the answer at once. If one of the X-ray photons happens to hit an electron that is bound to its atom with an energy less than the energy of the incoming photon, then the whole energy of the photon may be transferred to the electron. The latter must then fly out of the atom with an energy that is just the difference between the energy of the incoming photon and the binding energy of the electron within the atom.

[The photographs opposite page 618 enable one to see directly this photoelectric effect with X rays. The zigzag lines are the actual tracks of such electrons ejected from the atoms of the gas in the cloud chamber by the narrow pencil of X rays that enters through a slit on the right. (See arrow.) The total length of each track is a measure of the energy with which each electron left its atom. The zigzag character of the line is due to the fact that an electron having an energy of but from 5000 to 10,000 electron volts, such as the electrons shown here, is easily deflected as it goes past the electrons and the nuclei belonging to the atoms through which it passes. When, however, the energy is as high as 30,000 electron volts (see opposite page), the tracks are longer and straighter, and they become increasingly longer and straighter as the energy increases. These photographs are the most direct and convincing evidence for the correctness of the light-dart theory of radiation. It will be seen that the tracks all start from the narrow line along which the pencil of X rays goes through the chamber. The beginning of each line is the point at which the collision of a photon with an electron occurred. In such photoelectric absorption the whole energy of each photon is transferred to the absorbing electron, so that it is only the presence of the electron tracks which start within the chamber

itself that apprises us of the fact that photons were passing through the chamber at all. In other words, in photoelectric absorption, photons ionize a gas only indirectly through transferring their energy in a single act to electrons. These electrons, however, fritter away their energy continuously in producing ions all along their paths. There is, however, a second kind of absorption of photons by *free* electrons in which only a portion, though in general a large portion, of the energy is transferred; but this need not be further discussed here.

[Cosmic rays. Ten years ago no one had ever measured the energy of a photon that exceeded 2.6 million electron volts, and even the energies of the alpha and beta rays of radium, measured (as in Fig. 522) by their deflectabilities in strong magnetic fields, had not been found to exceed ten or twelve million electron volts. Ever since 1910, however, evidence had been accumulating to the effect that there is a radiation from outer space, coming into the earth equally from all directions, which is much more penetrating and presumably also much more energetic than any radiations that have their origin in the earth.

[In 1931 not only were these rays made visible through a new modification of the cloud-chamber technique, but their energies were directly measured and found to run from a few million electron volts up to the stupendous values of at least ten or twelve billion (thousand million) electron volts, or a thousand times higher than any individual ray energies theretofore known.

[These measured energies are the actual energies of the electron tracks found in specially constructed Wilson cloud chambers. Whether these tracks represent charged particles, such as electrons, that have come in from outside the atmosphere and then entered the cloud chamber, or whether they have arisen from the absorption of incoming photons by atoms within the atmosphere, cannot in all cases be determined. Both origins undoubtedly occur; but just what fraction of the observed tracks have the one origin, and what the other, is not yet determined. For our present purpose the

intensely interesting and significant thing is the mere discovery that we here on earth are being subjected to a continuous bombardment from all parts of the sky and that some eight or ten such electron shots as that shown in the right-hand panel opposite page 613, each of an average energy of a billion electron volts, go through every human head per minute.

[**How ray energies are measured.** The energies of the individual electron bullets are measured as follows: A very powerful horizontal magnetic field is applied at right angles to the path of the cosmic-ray electrons as they shoot through a vertical cloud chamber. From the measured curvature imparted to the track, the known charge of the electron, and the known strength of the magnetic field, the energy of the speeding electron in electron volts can be directly computed; the direction of the curvature shows whether the particle carries a positive or a negative charge. Thus the cosmic-ray track on the right panel opposite page 613 can be seen to be slightly curved to the left. This means that in the existing field of 20,000 gausses it is a negative electron; the existing curvature means that it has an energy of about 1.3 billion electron volts.

[**The discovery of the free positive electron.** It was through measuring the energies of cosmic-ray tracks that the free positive electron was discovered by Dr. Carl Anderson in August, 1932. We have already seen that all the free positive electricity within an atom is concentrated in its nucleus, so that we may be quite sure that if a cosmic-ray photon or, for that matter, a cosmic-ray electron knocks a positive charge out of an atom it must do so through a nuclear encounter. The photographs opposite page 622 show that some kind of nuclear encounter has given rise to electron tracks all exactly alike, save that some of them turn to the right and some to the left. Clearly positive and negative electrons have resulted from both nuclear encounters.

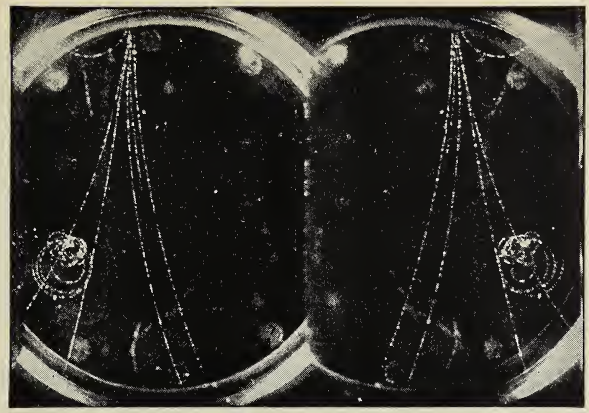
[The photograph opposite page 375 shows even more clearly how positive electrons are produced; for here the

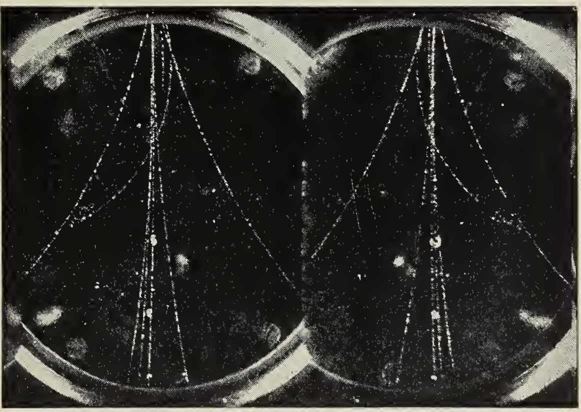
encounter takes place inside the lead bar that has been placed across the middle of the chamber. Since there is no electron track entering the top side of the central strip of lead from the direction in which the shower of tracks emerges from its bottom side, it is here quite certainly a *cosmic ray* that makes collision with a nucleus of a lead atom and thereby causes at least five positive and ten negative electrons to shoot downward. The powerful magnetic field then causes the positives to bend to the right, the negatives to the left.

[By artificially producing nuclear transformation, as described on page 624, it has now been found possible to form new radioactive atoms which emit from their nuclei positive electron rays of about the same energies and rates of decay as those exhibited by the negative beta rays of ordinary radioactive atoms.

[**The structure of the nucleus.** The discovery of the positive electron, or positron, has forced us to change our conception of the structure of the atomic nucleus. We formerly supposed that the proton, or hydrogen nucleus, was itself the ultimate unit of positive electricity, and we imagined all nuclei built up out of a number of protons equal to the atomic weight of the atom, and cemented together into a nucleus by a number of negative electrons equal to the atomic weight less the atomic number. But this was all changed by the discovery of the existence of a positive electron which is not at all associated with the mass of the proton, but is rather the twin of the light negative electron and therefore has a mass $\frac{1}{1836}$ that of the proton. This discovery, of course, means that the proton cannot itself be the ultimate unit of positive electricity. The discovery described in the next paragraph tells us something still further about the structure of the nucleus.

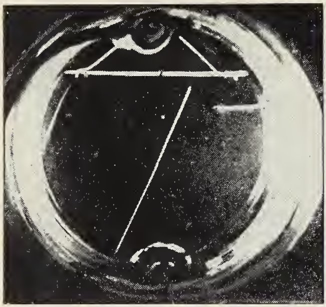
[**The discovery of the neutron.** The discovery of the neutron, made by Chadwick in England, actually preceded by about six months the discovery of the positron by Anderson. The steps leading up to this discovery, taken by Bothe in Germany and by Curie-Joliot in France, will here be omitted; but the net result is that when the alpha rays of radium





Positive and Negative Electrons from Cosmic-Ray Nuclear Encounters

In the upper picture a 500,000,000-electron-volt cosmic ray hits a nucleus of an atom in the brass piece above the chamber, and three positive and three negative electrons result (positive bend to the right in the direct left-hand image). In the lower picture a 2,000,-000,000-electron-volt ray makes another nuclear hit and produces two positives and six negatives. These pictures were taken with the apparatus shown opposite page 334. (See also pages 329 and 375)



(*a*)

(*b*)

(*c*)

Neutron Tracks Photographed by M. Joliot and Irène Curie-Joliot

(*a*) A neutron entering the chamber from above traverses a plate of paraffin extending across the upper part and ejects from it a proton (H^1) which shoots clear across the chamber. (*b*) The chamber is here filled with helium. A neutron entering from above collides with a He nucleus four times its own mass and can impart to it a range of only about 5 millimeters. (*c*) The neutron here causes the transmutation of a nitrogen nucleus which it enters and by so doing occasions the ejection of an alpha particle, while the heavy short trajectory reveals the recoil of the remainder of the nucleus. The pressure was here low and the magnification large

collide with the nuclei of certain atoms, notably those of beryllium, a body called a neutron is knocked out of the nuclei. The neutron is apparently just a trifle heavier than the proton, and is uncharged.

Since the neutron has no electrical charge, it cannot easily ionize a gas. It is able to shoot through the interior of atoms much more easily than can a charged particle. Moreover, if it is shot into a cloud chamber containing hydrogen, its rare collision with a hydrogen nucleus causes an easily visible proton track to originate at the point of collision. From such experiments and others of a similar sort the properties of the neutron have been determined. It is thought by some to be a primordial thing to which a positive electron must become closely attached in order to make a proton. Others prefer still to regard the proton as a primordial thing and to consider the neutron as a very intimate union of a proton and a negative electron. Experiment may some day be precise enough to distinguish between these alternatives. In any case, through the discovery of the positive electron we have been forced to assume the existence of three fundamental things, instead of two, the negative electron and proton, as formerly. Two of these are the positive and the negative electron; the third may be either the neutron or the proton. If the neutron is fundamental, the proton must consist of a neutron and a positive electron. If the proton is fundamental, the neutron must consist of a proton and a negative electron.

It has now become customary to regard the nuclei in all the 92 elements as built from a number of protons equal to the atomic number of the element in question and, in addition, a number of neutrons equal to the difference between its atomic weight and its atomic number. Thus oxygen has an atomic weight of 16 and an atomic number of 8. It would then contain 8 protons plus 8 neutrons. Uranium, atomic weight 238, atomic number 92, would contain 92 protons plus 146 neutrons.

The transmutation of the elements. Since an element is defined simply as an atom whose nucleus contains a given number of unit positive charges from 1 to 92, to produce trans-

mutation (change) from one element into another requires merely a change in this number. Thus, when a radioactive atom throws out a single negative electron, or beta particle, from its nucleus, the positive charge on its nucleus is increased by 1, and it therefore becomes the element of next higher atomic number. Similarly the loss of an alpha particle, which carries away 2 unit positive charges, changes it into the element two places farther down in the table of atomic numbers.

[Very recently physicists have learned to produce such transmutation of the elements artificially, first by simply shooting the nuclei of hydrogen and helium atoms into the nuclei of other atoms. Cockroft in Cambridge, England, Lauritsen in Pasadena, and Lawrence in Berkeley have in this way changed a very considerable number of the lighter elements into other light elements. The heavy elements cannot be changed in this way, because the positive charge on the nucleus of such an element repels too strongly, and therefore keeps out, protons and helium nuclei. But neutrons carry no charges, so that first Fermi in Rome and now many others have succeeded in transmuting the heavy elements by shooting neutrons into their nuclei. Indeed, it seems probable that elements in nature are continually being slowly transmuted into other elements through the penetration of neutrons into nuclei.

[**Isotopes.** Each of the ninety-two elements is characterized by its atomic number (see page 614), that is, the number of elementary positive charges on its nucleus. But most of the elements may have more than one atomic weight. These different forms are identical in chemical characteristics and are called *isotopes* of the element. Thus ordinary lithium, atomic number 3, consists of lithium of atomic weight 7 and a smaller amount of lithium of atomic weight 6. Chlorine has two isotopes of atomic weight 35 and 37. Neon has three of atomic weight 20, 21, and 22. Sodium, fluorine, nitrogen, and aluminum are single. The last four of the ninety-two elements have recently been measured by A. J. Dempster,

of The University of Chicago. He finds that gold is single, platinum has five isotopes, and palladium six. Iridium, the last of all the elements to be analyzed, consists of nearly equal quantities of two isotopes of weights 191 and 193.

{In 1931 H. C. Urey, of Columbia University, discovered that, in addition to ordinary hydrogen of atomic weight 1, there is present in ordinary hydrogen gas and in water (H_2O) a small amount of hydrogen of atomic weight 2, to the extent of about 1 part in 8000. This is popularly known as heavy hydrogen, but it has been given the scientific name *deuterium*, and its nucleus is called the *deuteron*. For this discovery Urey was given the Nobel prize in 1934.

{The nucleus of heavy hydrogen, the deuteron, must have a charge plus 1 and an atomic weight 2. This could, of course, happen in several ways, but the deuteron probably consists of one proton and a neutron. The deuteron has proved to be considerably more efficient than the proton in causing transmutation of some of the lighter elements.

{**The discovery of the mesotron.** The last new particle to enter the physics family is the mesotron (intermediate particle), so named because its mass is intermediate between that of the electron and the proton. The mesotron is like the electron in carrying either a positive or a negative electronic charge. It is unlike it in being about 200 times as massive. It is because of that massiveness that it can shoot like a bullet through many centimeters of lead without losing much energy, whereas an electron, because of its lightness, cannot do this because it necessarily fritters away its energy in producing *electron showers* within the lead. The cosmic-ray photograph opposite page 375 strikingly shows these two properties of the electron and the mesotron. An electron shower formed within the lead is seen emerging from the lower side of the central lead bar, and a half-inch to the right of this central shower is seen the track of a mesotron shooting straight through the lead bar without producing any showers or secondary tracks at all. This photograph was taken in the fall of 1933, and in 1934 Anderson and Neddermeyer in their report to the London Con-

ference on Nuclear Physics called attention sharply to this remarkable difference in the penetrating power of some tracks and the lack of it in others; but it was not until the fall of 1936, after they had made careful measurements for two years on the penetrating powers and momenta of many hundreds of tracks, that they made public announcement of the existence of a new penetrating particle which is produced in some way by the impact of cosmic-ray photons (or electrons) of enormous energy on the nuclei of the atoms within our atmosphere.

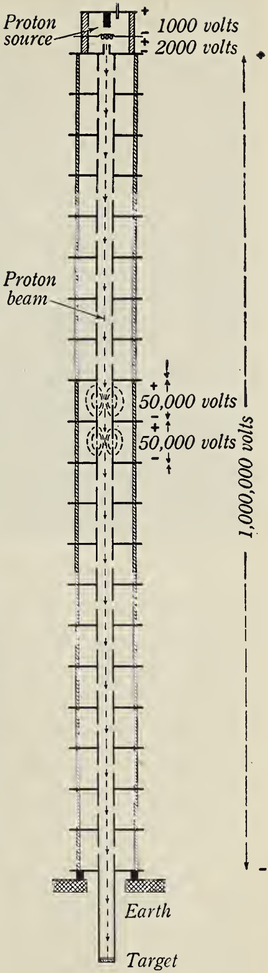
{**The aim of science.** As our knowledge of physics increases, we realize more and more surely that there is a wonderful unity in nature, and that knowledge about some apparently unimportant detail may have tremendously important consequences. Modern engines could not have been built without a knowledge of the foundations of mechanics, which we owe to Galileo and Newton. The modern dynamo owes its existence to Faraday's apparently unimportant discovery that a current of electricity is caused to flow in a loop of wire when the magnetic field through it is changed. What appeared to be a purely mathematical deduction of Maxwell, the electromagnetic theory of light, led Hertz and Marconi to the beginnings of wireless telegraphy; and Edison's apparently unimportant discovery that charged particles (electrons) are given off by a hot wire led to the modern electron tube and the almost unbelievable wonders of modern radio.

{The spirit of science, then, impels us to search for truth in nature, and to understand the things observed, without special thought of how much or how little importance the results may seem to have. It becomes increasingly clear as science advances that all knowledge is important, and to the true scientist it is sufficient that the truth he finds should be important to him, in the sure faith that future generations will fit this truth into its proper place. Surely the future holds in store the promise of new wonders equal to those of the past and present.

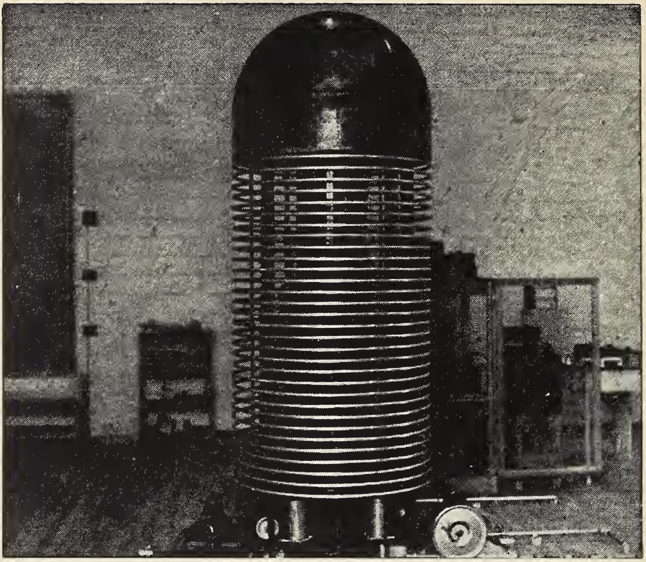
The key to the operation of practically all modern atom-smashing machines was found not at all in learning how to produce potentials of millions of volts (physicists have known how to do that for fifty years) but rather in *learning how to build vacuum tubes, or chambers, which can stand such potentials without puncturing or otherwise breaking down* — tubes in which charged particles not only can be given millions of volts of bombarding energy but also can be accurately controlled and directed against the small target on which lie the atomic nuclei to be smashed and transmuted.

This feat was first successfully accomplished by Charles C. Lauritsen and his coworkers in 1928. The essence of the device consisted in placing a considerable number of insulated, hollow, metal cylinders in a row inside the evacuated glass tube through the ends of which passed the electrodes to which the high P.D. was to be applied. In this way the available potential was distributed into as many steps as there were cylinders. With suitable evacuation no chance was then given for the development of a very large puncturing P.D. between the inner and outer sides of the glass wall. It was thus that the first "million-volt X-ray tube" was constructed after a quarter-century of effort had reached only to a potential of 300,000 volts.

In later forms of the Lauritsen "million-volt" tube designed for bombarding a target with protons, for example, the procedure is as follows: A very little hydrogen is first let into the small upper chamber, which is completely closed save for the very narrow canal just below the filament. When the heating of this filament releases the electrons which ionize this hydrogen the positive ions, or protons, are pulled by the field through this canal and start down the big tube, which is kept evacuated by the continuous action of powerful pumps down to a pressure of the order of a millionth of a millimeter of mercury. If there are 20 cylinders, as shown, the net result is that the protons receive 20 successive kicks as they pass through the spaces between each pair of successive cylinders and hit the target at the bottom with the energy of the full applied million or millions of electron volts. They have also supplied most of the neutrons which made possible the new discovery (1939–1940) as to the power released in the fission of the 235 uranium isotope

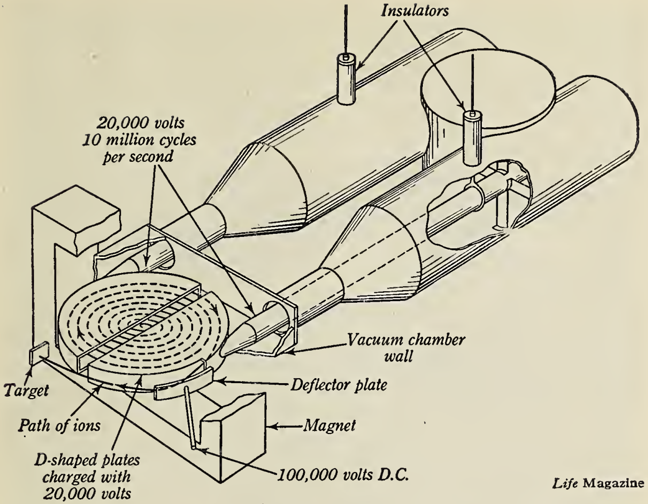


Atom-Smashing Machines



The Simplest Form of Atom-Smashing Machine

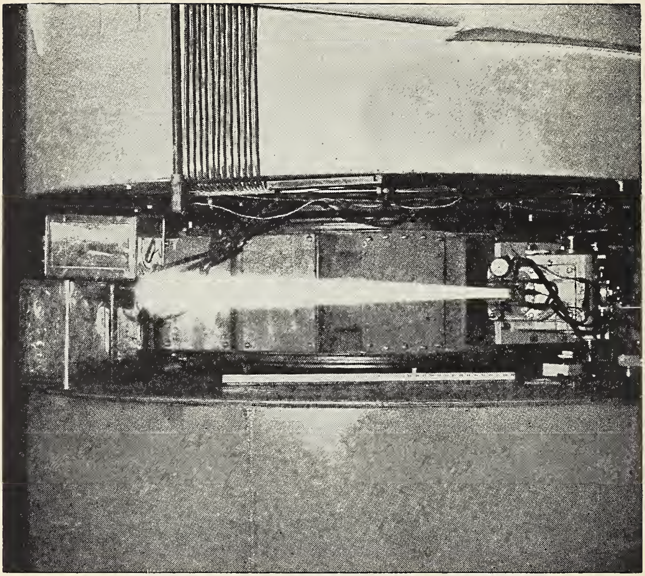
The P. D. between the hemispherical dome at the top and the ground is here produced by a static machine of the so-called Van de Graaff type, which does not differ in principle from those shown on page 332. Rapidly running rubber belts just inside the metal rings have positive charges sprayed on them at the bottom from sharp points raised to potentials at which they ionize the air in front of them, and these positive charges are carried vertically up by the belts and deposited on the dome, which because of its great size can be raised to a high potential before its charge begins to leak off. Indeed, when the whole machine is placed inside a pressure tank and five atmospheres of air pumped in (Herb of Wisconsin did this first) a three-foot dome can be raised to a potential of 4 million volts, enough to smash the nucleus of any known atom. This potential is controlled and the proton or deuteron or electron beam directed to its target by one of the now universally used Lauritsen tubes which can be seen in the middle through the rings. Each of these rings is connected to one of the inner metal cylinders of the Lauritsen tube described on the other side of this leaf, so that the P. D. is distributed uniformly by a series of steps equal to the number of rings (or cylinders). The target is in this case at the bottom of a brass tube of 1 inch diameter, which runs from the bottom of the Lauritsen tube through the floor into the room below, where fluorine atoms are here being transmuted into oxygen and helium. In simplicity, economy, and the accuracy and dependability of its findings this type of atom-smasher is unrivaled.



The Most Powerful Atom-Smasher save for the Cosmic Ray

The most powerful *man-made* atom-smasher is the cyclotron, though even it is capable of firing a bullet into a nucleus with an energy of at most but 1 per cent of that with which cosmic rays are all the time smashing into atomic nuclei as they plunge from outer space into our atmosphere. In principle the cyclotron is very much like Lauritsen's high-potential tube. For while in the latter the high energy is imparted to a proton or other charged particle by letting it get a new kick forward as it goes through the electric field between the ends of each adjacent pair of a long straight row of metal cylinders, in the cyclotron a powerful magnetic field forces the particle to spiral around and emerge at the periphery, as shown in the diagram. The magnetic lines of force of the magnet are at right angles to the plane of the paper. The particle thus shoots through the electric field between the D-shaped plates many times, thus building up its kinetic energy with the aid of more kicks than a straight row of cylinders can conveniently develop. This electric field must of course be alternating and very accurately timed so that it always kicks the proton in the right direction.

With this device Dr. Ernest Lawrence, who in 1939 received the Nobel prize for this development, has attained particle energies as high as 19 million electron volts, and he is now building a cyclotron with a 4000-ton magnet with which he hopes he may be able to obtain particle energies as high as 100 million electron volts. These atom-smashing devices are of great scientific interest because of the light they throw on nuclear transformations. Their main practical use so far is in producing artificial radioactive substances which have been found helpful to the physiologist (see next page)



A 16-million-volt beam of deuterons emerging through the target window of a cyclotron into the air for a distance of four and a half feet. The poles of the huge magnet are above and below

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